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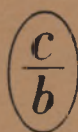
March, 1994

LITHOLOGY AND MINERAL RESOURCES

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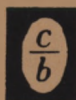
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LITHOLOGY AND MINERAL RESOURCES

A translation of *Litologiya i Poleznye Iskopaemye*

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6/29/1993. Publication therefore did not occur prior to this date, but
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COMPARATIVE ANALYSIS OF QUANTITATIVE COMPOSITION AND DISTRIBUTION PARAMETERS OF FORMATION GROUPS, EAST EUROPEAN AND OTHER ANCIENT PLATFORMS OF THE WORLD

A. B. Ronov and A. A. Migdisov

UDC 551.8:551.263.1

Quantitative characteristics of the composition and volume distribution of the most important lithological units of the sedimentary cover in the East European Platform were compared with these parameters in other old platform areas worldwide. By marking differences and similarities between platforms an attempt at global ranking of platforms also involved the East European Platform.

In addition to with geosynclines and orogens, platforms represent global tectonic structures that participated in the formation of continents. Ancient and new platforms exist. The East European Platform is an ancient one. Globally, there are nine major ancient platforms; three in Asia (Siberian, Chinese, and Hindustan Platforms); one each, in the other continents.

Ancient platforms are huge continental lithospheric blocks, outlined by deep marginal faults that separate them from geosynclines and orogenic belts [23]. In the platforms the sedimentary blanket overlies the crystalline basement with a sharp unconformity. Geophysical data indicate that the basement consist of granite-metamorphic and underlying granulite-basite layers.

Ancient platforms include four high-order structural elements: shields, plates, graben-type basins (aulacogens) and marginal synclises. A number of young plates became attached to them as the folded basement and the ancient platform became combined and the platforms consolidated.

Shields lack sedimentary cover. Precambrian crystalline rocks form the surface. Folding, metamorphism and intrusions characterize the preplatform consolidation stage. The absence of sedimentary rocks resulted from prolonged and stabilized crustal uplifts, resulting in shield erosion. Rare thin sedimentary beds indicate brief periods of subsidence.

Plates of the Precambrian crystalline basement subsided to varying depths at different localities. Sedimentary rocks of various ages and lithology cover the basement. The sediment blanket is the result of a prolonged, steady basement subsidence. Uplifts periodically destroyed the sediment blanket. Consolidation of the ancient basement took place in mid-Proterozoic times, while the oldest sediments were deposited in the early Upper Proterozoic.

Grabenlike depressions (aulacogens) are represented by intensive subsidence of linear structures that stretch to significant distances. They were active during the Late Proterozoic and Paleozoic for more than a billion years. Thick Riphean, Lower Vendian, and in some aulacogens, also Paleozoic beds formed, mostly through terrigenous genesis. Aulacogen stages alternated with plate-type development during the Late vendian in large areas of the East European Platform.

The ancient Russian Plate occupies vast areas in eastern Europe (3.2 million km²). Its sediment blanket, represented by Upper Vendian deposits and all of the Paleozoic, Mesozoic and Cenozoic systems, overlies either the Precambrian crystalline basement or Riphean and Lower Vendian deposits in grabenlike depressions.

East European and other ancient platform plates display the following first-order structural elements:

(a) *Massifs*. The crystalline basement, as in the Voronezh Massif, extends close to the land surface and is overlain by thin deposits; (b) *Anteclises*. These are large and very gently sloping uplifts (e.g., Volga–Ural Antecline). The sediment cover is thin. Significant interruptions occurred during sediment deposition. Continental and coastal deposits are widespread; (c) *Synclises*. Large and very gently-sloping depressions (e.g., Moscow Syncline). The sediment cover is thicker than in anteclises. The number of unconformities is reduced and marine deposits dominate.

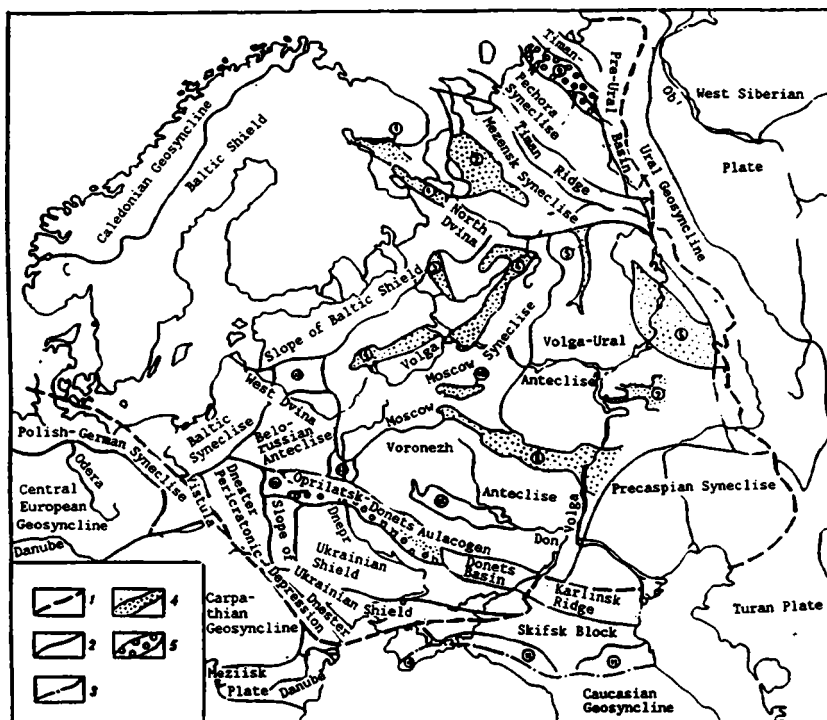


Fig. 1. Major structural elements of the East European Platform: 1) platform boundary; 2) boundary of the basic platform structure; 3) south boundary of the Skifsk Plate; 4-5) aulacogens (4 - Precambrian; 5 - Paleozoic). Numbers in circles: structure: 1-9) aulacogens (1 - White Sea; 2 - Leshukonsk; 3 - Vazhe-Lachsk; 4 - Central Russian; 5 - Katimsk; 6 - Kaltasinsk; 7 - Sernovodsk-Abdullinsk; 8 - Pachelmsk; 9 - Pechora-Kolvinsk); 10) Moscow Syncline; 11) main Precaspian basin; 12-14) saddles (12 - Latvian; 13 - Zhlobinsk; 14 - Polessk); 15) Voronezh Massif; 10) Crimean Geosyncline.

Anteclises and synclises that developed during long time periods in the Russian Plate, formed during a single tectonic cycle, occasionally a number of tectonic cycles. Their distribution pattern changed occasionally from one cycle to the next. Anteclises, as the result, occupied broader subsidence zones, while synclises were confined to uplifts [23].

Marginal Synclises. These are large, deeply downfolded flexure basins along plate margins in pericratonic belts of subsidence. Concentric flexures or fractures separated them from plates. Marginal synclises differ in terms the age of the folded basement. The following two units occur in the East European Platform:

(A) **Ancient Precaspian Syncline.** Upper Proterozoic and Phanerozoic deposits form the cover. The sedimentary section locally reaches 20 km or more. Geophysical data indicate that the deposits overlie Precambrian crystalline basin, while a wedge of apparently granitic-metamorphic units is exposed in the central area. Deep drilling encountered only Mesozoic-Cenozoic, Upper and Middle Paleozoic rocks.

(B) **Young Marginal Synclises** (Pechora, Pol'sk-Litovsk and Valakhian Basins). Sediment thickness exceeds 10 km. The deposits either formed or were reworked in the Baikal Epoch. Occasionally, they overlie the Paleozoic basement [13].

Young Plates. In the East European Platform, the Skifsk Plate, with a 0.25 million km² area belongs here. Its sedimentary cover is 200 Ma old. Mesozoic and Cenozoic deposits cover the Hercynian folded basement. After Hercynian geosynclinal folding was completed, the Skifsk Plate was fused to the East European Platform on the south.

AREAS, VOLUMES, MEAN THICKNESS VALUES OF THE SEDIMENTARY COVER, EAST EUROPEAN PLATFORM

The ancient East European Platform occupies a significant part of eastern Europe and forms an irregular polygon, separated by marginal faults from surrounding geosynclines (Fig. 1). Its contours on the northeast were determined by

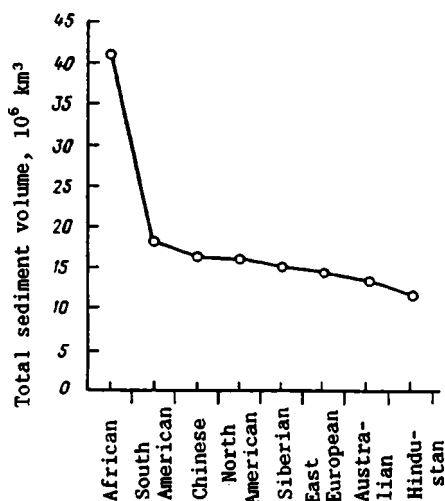


Fig. 2

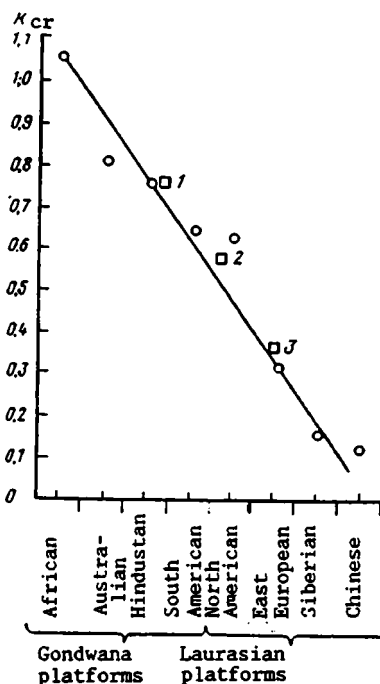


Fig. 3

Fig. 2. Distribution of total Neogene sediment volume values among ancient platforms worldwide [13].

Fig. 3. Changed cratonization coefficient values in the sequence of ancient continental platform areas: 1-3) mean values for Gondwana Platform (1), all ancient platforms (2) and Laurasian Platforms (3).

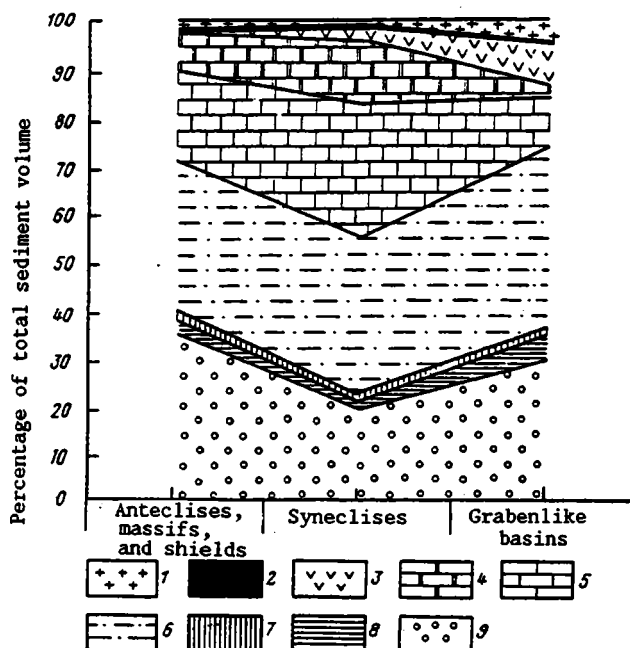


Fig. 4. Distribution of Neogene formation groups in main structural zones of East European Plate. Formation groups: 1) volcanogenic (trap); 2) siliceous; 3) salt and gypsum-bearing; 4) dolomitic; 5) limey; 6) marine sandy-clayey; 7) bituminous shales and marls; 8) coal-bearing; 9) continental sandy-clayey.

TABLE 1. Quantitative Parameters of Continental Platforms Worldwide

Platforms	Total sediment volume, 10^6 km^3	Area, 10^6 km^2		Coefficient of cratonization, Kcr	Mean sediment thickness, km	Mean platform burial rate during the Neogene, m/Ma	Formation distribution (percentages of total deposit volume)									Maps used for calculations
		shields and crystalline massifs	shields and marginal synclises				continental sandy-clayey	coal-bearing	glacial	marine sandy-clayey	total of terrigenous formations	carbonate	salt-bearing	siliceous	continental volcanic	
African	40,7	10,0	9,4	1,06	4,3	2,6	29,4	0,8	0,5	42,2	72,9	19,9	2,2	-	5,0	[15, 16]
Australian	13,0	2,2	2,7	0,81	4,8	2,9	20,2	5,2	0,2	52,5	78,1	18,9	0,2	-	2,8	-
Hindustan	11,8	1,5	2,0	0,75	5,9	3,6	12,2	0,9	1,3	46,8	61,2	24,3	0,4	-	14,1	-
South American	18,1	4,9	7,6	0,64	2,4	1,4	40,0	2,9	0,1	37,7	80,7	10,9	0,6	0,1	7,7	-
Subtotal Gondwana platforms	83,6	18,6	21,7	0,86	3,8	2,3	27,8	1,9	0,5	43,6	73,8	18,4	2,7	0,02	6,5	-
North American	16,2**	4,6****	7,3	0,63	2,2	1,3	10,8	2,1	0,1	48,6	61,6	33,6	2,7	0,03	2,1	[15, 16, 26]
East European	14,4***	1,3	4,2	0,31	3,4	2,1	21,3	1,7	0,1	31,6	54,7	36,1	8,2	0,1	0,9	[1, 2, 20]
Siberian	14,5	0,6	3,9	0,15	3,8	2,2	10,1	4,8	0,1	32,5	47,5	40,2	9,7	-	2,7	[3-6, 20]
Chinese	16,4	0,5	4,0	0,12	4,1	2,5	24,8	2,8	-	37,3	64,9	32,2	0,4	0,3	2,2	[15, 16]
Subtotal Laurasian platform	61,5	7,0	19,4	0,36	3,2	1,9	16,8	2,8	0,1	37,8	57,5	35,4	5,0	0,1	2,0	-
All ancient continental platforms*	145,1	25,6	41,1	0,57	3,5	2,1	23,1	2,3	0,3	41,2	66,9	25,5	2,9	0,1	4,6	-
All ancient and young continental platforms	235,0	30,0	65,0	0,46	3,6	2,2	20,5	2,4	0,2	38,7	61,8	30,9	3,3	0,3	3,7	[15, 16]

*Excluding the Antarctic Platform.

**Including the sediment volume of the Gulf of Mexico and Atlantic coastal plains.

***Including the volume of the Precaspian plain and the marginal syncline.

****Excluding Greenland.

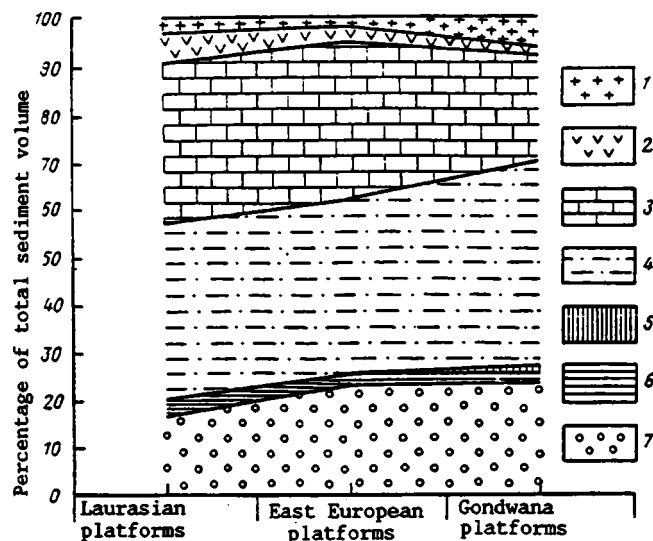


Fig. 5. Comparison of mean distribution of lithologic units, East European Platform, with mean values for the total, in combining Laurasian and Gondwana Platforms. Formation groups: 1) continental volcanics; 2) salt-bearing; 3) carbonates; 4) marine sandy-clayey; 5) glacial; 6) coal-bearing; 7) continental sandy-clayey.

the marginal fault of the Baikal geosynclinal system; on Rybachii-Timan Peninsula on the east, by the Baikal-Hercynian geosynclinal system of the Ural; on the south by the Paleozoic Precaucasian and Crimean geosynclines; on the southwest by the geosynclinal systems of Dobrudzha, the Paleo-Carpathians and the Sudeten chain; on the northwest, by the Baikal-Caledonian geosynclines of Scandinavia [23]. Within these limits, the East European Platform occupies a $5.51 \cdot 10^6$ km² area, of which $1.16 \cdot 10^6$ km² occurs in the Baltic Shield, $0.14 \cdot 10^6$ km² in the Ukrainian Shield; $3.21 \cdot 10^6$ km² in the East European Plate; $0.48 \cdot 10^6$ km² in the adjacent ancient Precaspian marginal syncline; $0.25 \cdot 10^6$ km² in the Pechersk Basin with the Baikal folded basement; $0.18 \cdot 10^6$ km² in the Pol'sk-Litovsk Basin with the Baikal, Caledonian and Hercynian folded basement, and, finally, $0.09 \cdot 10^6$ km² in the Valakhsk Basin with the Baikal folded basement [13].

These were the limits within which the volume of the sediment cover of the East European Platform has been established. It was measured by the tectonophysical method [13] by using basement relief charts of the USSR [20] and Poland [28]. Corrections of the sediment volume above sea level were prepared by the physical geographic chart of the European sector of the USSR. The volume was measured as $14.35 \cdot 10^6$ km³ [22], unevenly covering the platform area. In the Russian Plate the sediment cover volume is $6.5 \cdot 10^6$ km³; its mean thickness, c. 2 km. In the Precaspian Basin, with an area one-seventh of the Russian Plate's, the sediment volume ($5.65 \cdot 10^6$ km³) is only slightly smaller. The mean sediment thickness is 11.8 km. The total sediment volume of the Pechora Basin is $0.75 \cdot 10^6$ km³; mean thickness, 3 km. The Pol'sk-Litovsk Basin has a volume of $0.85 \cdot 10^6$ km³; mean thickness, 4.8 km; the Valakhsk Basin, $0.54 \cdot 10^6$ km³, mean thickness, 6 km [13].

Traditional assumptions about the East European Platform as an area of uplift or of very slight subsidence, are thus only partially correct. In proportion to the disappearance of geosynclinal conditions, depressions developed along the margins of ancient platforms. They inherited the tendency from the previous periods for steady and fast crustal subsidence. The basin acted as a gigantic sediment trap, accumulating huge sediment volumes. The total volume in the peripheral basins of the East European Platform ($7.79 \cdot 10^6$ km³) exceeds the total sediment volume of the plate sector ($6.56 \cdot 10^6$ km³) and slightly exceeds the total sediment volume of the Russian and Skifsk Plates ($7.26 \cdot 10^6$ km³).

Results of measurements of the total volume of Russian Platform sediments were based on a series of lithological-paleogeographic charts from the Atlas of the East European Platform and its geosynclinal margins [1, 2]. These supplied values very close to those, produced by the tectonophysical method [13]. However, volume calculations from the Atlas of the East European Platform and its marginal basins have been greatly reduced [13] because lower horizons of the sediment blanket occur at great depths in the basin, unexplored by drilling. Consequently, rock volume measurements were avoided for such basin area in the paleotectonic and lithological-paleogeographic maps [13].

TABLE 2. Comparison of Volumes, Mean Thickness Values of Sediments and Mean Accumulation Rates of Sediments, Eastern Europe, North American and Siberia Platforms

Platforms	Large structural platform zones		Area, 10^3 km^2		Sediment volume, 10^3 km^3			Mean thickness of sediment cover, m	Time span of sedimentation, Ma	Mean deposition rate, mm/ka	Maps used in calculations
			outcrops on Precambrian crystalline rock surface	area of sediment cover	vertical distance between basement surface and sea level	vertical distance between sea level and land surface, m	total volume				
1	2		3	4	5	6	7	8	9	10	11
East European	Shields	Baltic	1160	-	-	-	-	-	-	-	Internal Tectonic Chart of Europe [10]
		Ukrainian	140	-	-	-	-	-	-	-	
		Both shields	1300	-	-	-	-	-	-	-	
	Ancient platform with Precambrian crystalline basement	Russian plate	-	3210	6100	460	6560	2044	1650	1,2	Tectonic Chart of Hydrocarbon Zones of the USSR [20] and basement map of Poland [27]
		Precaspian basin	-	480	5640	10	5650	11800	1650	7,1	
		Ancient East European platform	-	3690	11740	470	12210	3310	1650	2,0	Tectonic Chart of Hydrocarbon Zones of the USSR [20]
	Post-Baikal peripheral synclises	Pechersk and Baikal folded basement	-	252	710	40	750	2980	~500	6,0	Tectonic Chart of Hydrocarbon Zones of the USSR [20]
		Balakhsk and Baikal folded basement	-	94	520	20	540	5745	~500	11,5	Tectonic map of Skifsk and Miziisk Platforms [9]
		Pol'sk-Litovsk, with Hercynian basement	-	178	820	30	850	4775	~600	8,0	Tectonic Chart of Hydrocarbon Zones of the USSR [20] and basement map of Poland [27]
		Total young peripheral synclises	-	524	2050	90	2140	4084	-	7,7	
		Peripheral synclises, including the Precaspian	-	1004	7690	100	7790	7760	-	-	

		East European platform in general	1300	4214	13800	580	14350	3408	-	-	
		Skifsk plate with Hercynian plate	-	247	674	31	705	2854	180	15,8	Tectonic Chart of Hydrocarbon Zones of the USSR [20]
		East European platform and Skifsk plate	1300	4461	14474	591	15055	3362	-	-	
		Canadian shield	4600*	-	-	-	-	-	-	-	Tectonic Chart of North America [26]
		North American plate with Precambrian folded basement	-	6170	7650	4331	11981	1942	1650	1,2	Same
North American	Structures with Hercynian folded basement	Gulf Coast Basin (continental part)	-	980	4055	125	4180	4265	180	23,7	"
		Atlantic coastal plain	-	180	67	23	90	500	180	2,8	"
		Total of last two	-	1160	4122	148	4270	3681	180	20,4	
	North American platform, in general		4600	7330	11772	4479	16251	2217	-	-	
	Aldan shield		552	-	-	-	-	-	-	-	Tectonic Chart of Hydrocarbon Zones of the USSR [20]
Siberian	Shields	Anabar massif	62	-	-	-	-	-	-	-	Same
		Total of last two	614	-	-	-	-	-	-	-	
	Ancient plate with Precambrian crystalline basement		-	3480	12743	957	13700	3937	1650	2,4	"
	Relatively young parts of platform	Area with Baikal folded basement	-	260	400	40	440	1692	~600	2,8	
		Area with Caledonian folded basement	-	150	345	15	360	2400	~400	6,0	"
West Siberian	Siberian platform, in general		614	3890	13488	1012	14500	3727	-	-	
	plate with Hercynian folded basement		-	2270	5930	-***	5930	2612	~195	13,4	"

*Greenland excluded from Canadian Shield. Combined area of the two: $6.5 \cdot 10^6$ km².

**Sediment volume between sea level and land surface was based on Physical Geographic Atlas of the World [22].

***Due to the flat or very gently sloping surface, no correction made for sediment volume above sea level.

TABLE 3. Distribution of Formation Groups in Major Zones of Russian Plate

Main structural zones of the Russian plate	Total sediment volume, 10 ³ km ³	Distribution of formation groups (percentages of total deposit volume)								
		continental sandy-clayey	coal-bearing	marine sandy-clayey	bituminous shales, clays and marls	limey	dolomitic	salt and gypsum-bearing	siliceous	volcanogenic
Anteclises, massifs, and shield slopes	783	35,4	2,4	33,0	0,9	18,3*	7,7	—	0,8	1,5
Syneclises	4472	19,4	1,0	33,5	1,4	27,4**	13,7	3,4	0,1	0,1
Grabenlike	1513	30,3	4,8	38,1	1,2	10,2	4,0	6,9	—	4,5
Plate, in general	6768	23,6	2,0	34,5	1,3	22,5***	10,8	3,8	0,2	1,3

*Proportion of cretaceous: 3.1%.

**Proportion of cretaceous: 2.4%.

***Proportion of cretaceous: 1.9%

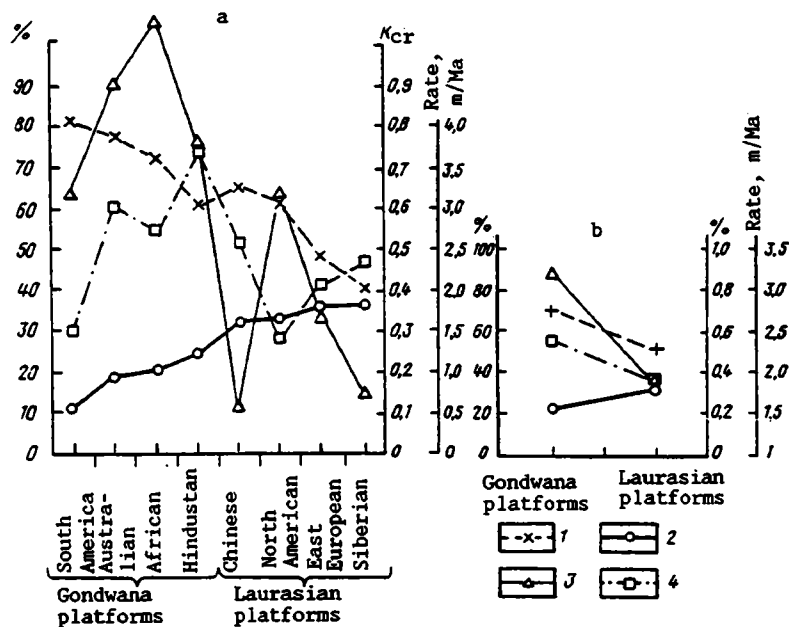


Fig. 6. Distribution of terrigenous (1) and carbonate groups (2) in units (percentage of total sediment volume in each platform), changes in K_{cr} -values and (3) mean burial rate of plate and marginal synclises; (4) in ranking of ancient continental synclises worldwide (a); changes in these values between combined Gondwana platforms and combined Laurasian platforms (b).

QUALITATIVE PARAMETERS OF THE EAST EUROPEAN PLATFORM AND OTHER ANCIENT LARGE PLATFORMS WORLDWIDE

The total volume of platform deposits in continents, including both ancient and young platforms equals $235 \cdot 10^6 \text{ km}^3$ [17]. $145 \cdot 10^6 \text{ km}^3$ of sedimentary and volcanic rocks occur in ancient continental platforms, excluding Antarctica (Table 1). The total sediment volume in Gondwana platforms ($84 \cdot 10^6 \text{ km}^3$) is greater than deposits in the Laurasian platforms ($62 \cdot 10^6 \text{ km}^3$). If ancient platforms are ranked by sediment volumes, the African Platform takes first place. $40.7 \cdot 10^6 \text{ km}^3$ of Neogene deposits accumulated here (Fig. 2). The next, South American Platform contains less than half of this volume ($18.1 \cdot 10^6 \text{ km}^3$). In the rest of the sequence the sediment volume declines slowly, ending with a $11.8 \cdot 10^6 \text{ km}^3$ minimum for the Hindustan Platform.

In comparison with the Laurasian platform group, the greatest Neogene volumes in the Gondwana platform group occur in the African Platform. During the Mesozoic an unusually large volumes accumulated here ($19.3 \cdot 10^6 \text{ km}^3$). This value may be overstated. Volume calculations of Mesozoic, especially Cretaceous deposits were based on literature data from African charts [16]. If one excludes the African Platform from the study, then the rest of Gondwana platform sediment volume ($14.9 \cdot 10^6 \text{ km}^3$) appears to be very close to the mean Laurasian Platform sediment volume ($15.5 \cdot 10^6 \text{ km}^3$) and the total for the Russian Platform ($14.4 \cdot 10^6 \text{ km}^3$). In terms of associated sediment volumes, the East European Platform appears to occupy an intermediate position among the oldest platforms worldwide. In terms of its mean Neogene thickness value (Table 1), the East European Platform occupies a comparable position globally. In terms of the Precambrian shield outcrop area ($1.3 \cdot 10^6 \text{ km}^2$), it is among the lowest ranked ancient platforms worldwide, followed only by the Siberian ($0.6 \cdot 10^6 \text{ km}^2$) and the Chinese ($0.5 \cdot 10^6 \text{ km}^2$) Platforms. According to this parameter and its area, the East European Platform resembles the Laurasian continent group and sharply contrasts with the Gondwana platform group (Table 1).

The greatest differences between the Laurasian and Gondwana Platforms are expressed by the total plate areas in the shield and marginal syncline areas (S_{plate}). This ratio, named cratonization ratio, K_{cr} , expresses a general quantitative relationship between areas of steady crustal uplift and subsidence in platform areas. A trend among ancient platforms,

displays gradual decline in the cratonization index (Table 1 and Fig. 3). Differences between extreme K_{cr} values amount to one magnitude order (The K_{cr} value in the African Platform is 1.06; in the Chinese Plate, 0.12). The Gondwana Plate displayed a maximum, the Laurasian Plate, a minimum value. This was determined by the predominance of crustal uplifts during the Neogene in the Gondwana and crustal subsidence in the Laurasian Plate Area. The East European Platform occurs on the descending branch of the cratonization curve ($K_{cr} = 0.31$), and approximates the mean cratonization value ($K_{cr} = 0.36$) for the Laurasian platforms. It differs sharply from the mean value of the Gondwana group ($K_{cr} = 0.86$).

The data justifies assumptions of many geologists. Bogdanov expressed these the best [8]: the East European Platform represents the tectonotype of all old platforms worldwide, it is "a representation of this crustal structure category. Armed with this example, we may review many questions that relate to the composition and evolution of these structures." In fact, the East European Platform should be regarded only as a "tectonotype" of the Laurasian platform group. In terms of certain parameters, however, it also reflects the overall characteristics of all ancient platforms worldwide.

Let us compare quantitative compositional parameters of the East European and other ancient Laurasian platforms; the North American and Siberian Platforms (Table 2). Measurements by the tectonophysical methods are employed by the use of tectonic charts from different regions [20, 22, 26].

The *ancient North American Platform* forms the continents's stable core. Its limits coincide with marginal faults of the adjacent geosynclines; on the east with the Caledonian–Hercynian system of the Appalachians, on the south the Ouachita–Marathon geosynclinal system, on the west the Rocky Mountains Geosyncline, on the north, the geosyncline of the Arctic Archipelago. Excluding Greenland, the total area of the North American Platform is $11.9 \cdot 10^6 \text{ km}^2$. $4.6 \cdot 10^6 \text{ km}^2$ of this is part of the Canadian Shield, composed of Precambrian crystalline rocks; $6.2 \cdot 10^6 \text{ km}^2$ part of the North American Plate with a sediment cover composed of Upper Proterozoic and Phanerozoic rocks, $1.0 \cdot 10^6 \text{ km}^2$ belongs to the marginal zone of the Gulf Coast Basin, and $0.2 \cdot 10^6 \text{ km}^2$ to the Atlantic coastal plain (Table 2). The figures indicate that the Platform is larger than the East European Platform. The plate area is twice, the shield area almost four times the size of corresponding areas in the East European Platform. However, the total volume of its sediment blanket is only slightly greater than the sediment volume of the East European Platform ($16.25 \cdot 10^6 \text{ km}^3$, vs $14.3 \cdot 10^6 \text{ km}^3$).

More than one-third of the North American Platform's total rock volume occurs above sea level, occasionally reaching +1000 in the southwest. Most East European Platform sediments (96%) occur below sea level and never reach above +500 m elevation.

The large volume of young (Mesozoic–Cenozoic) deposits accumulated in the marginal Gulf Coast Syncline. Deposits unconformably overlie a Caledonian–Hercynian folded basement here. $4.2 \cdot 10^6 \text{ km}^3$ sediment volume forms the exclusively continental part of the syncline (Table 2). The value probably doubles if sedimentary units of the southern syncline area under the Gulf of Mexico are added. The sediment volume in the continental portion of the Gulf Coast Syncline equals the sediment volume in the Precaspian Basin geosyncline ($5.6 \cdot 10^6 \text{ km}^3$). However, the mean thickness of the Gulf Coast Basin sediment sequence is only half of that of the Precaspian Basin (4.3 vs. 11.8 km); the sediment there occupy a much greater area ($0.98 \cdot 10^6 \text{ km}^2$, vs. $0.48 \cdot 10^6 \text{ km}^2$). In comparison with the Gulf Coast basin, Mesozoic and Cenozoic sedimentation in the Atlantic coastal plain was insignificant. $0.09 \cdot 10^6 \text{ km}^3$ of sediment accumulated here in the continental sector, with a mean thickness of 0.5 km.

In all, the total rock volume of the North American Platform ($16.2 \cdot 10^6 \text{ km}^3$) approximates that of the East European Platform ($14.4 \cdot 10^6 \text{ km}^3$). However, the North American Platform occupies a much greater area ($7.3 \cdot 10^6 \text{ km}^2$, vs. $4.2 \cdot 10^6 \text{ km}^2$). This accounts for differences in mean sediment thickness values in the platform covers (2.2 km, vs. 3.4 km).

The lesser subsidence rate of the North American Platform is related to the more intensive uplift of the Precambrian basement. As the result, the outcrop area of the ancient crystalline rocks in the Canadian Shield area is four times, including Greenland, five times greater than the Precambrian crystalline shield outcrop area of the East European Platform. Finally, while post-Hercynian sediments, deposited in the Gulf Coast Basin are known from the North American Platform, this type of deposition did not take place in young basins of the East European Platform (Table 2).

The *ancient Siberian Platform* is also outlined by a polygonal fracture system that coincides with marginal faults of adjacent geosynclines [24]. Its total area is $4.5 \cdot 10^6 \text{ km}^2$, of which $0.6 \cdot 10^6 \text{ km}^2$ occurs in the Aldan Shield and the Anabar Massif, $3.9 \cdot 10^6 \text{ km}^2$ in the ancient Siberian Shield and the younger platform basins (Table 2). The total sediment volume of the sedimentary blanket is $14.5 \cdot 10^6 \text{ km}^3$. Basins with young basement areas are insignificant in the Siberian Platform

($0.8 \cdot 10^6 \text{ km}^3$). Most of the sediment volume, dominantly of Riphean and Paleozoic age, occurs above the ancient crystalline basement ($13.7 \cdot 10^6 \text{ km}^3$) in the plate area. The mean thickness of the sediment blanket over the ancient plate (3.9 km) is twice that of the Russian (2.0 km) and the North American Plates (1.9 km). The outcrop area of Siberian Platform Precambrian crystalline rocks is half of these outcrops in the East European Platform and only one-eighth of that area in the Canadian Shield of the North American Platform. Its value is comparable with Chinese Platform shield areas (Table 1).

MEAN DISTRIBUTION VALUES OF NEOGENE FORMATIONS IN THE EAST EUROPEAN AND OTHER ANCIENT PLATFORMS

The composition of the sediment blanket of the East European Platform and other ancient platforms is varied. These sediments include rocks of various geological ages and lithological composition. They alternate and form given associations that replace each other, displaying variations throughout the section. Such associations are called formations in the hierarchy of lithological terminology. In agreement with Shatskii [21], they are considered the largest taxonomy units present in the sediment cover. Formation were defined by various classifications and principles in the domestic literature. They are based on paragenetic, genetic, dynamic, tectonic and other concepts [7, 11, 18, 19, 21, 24, 25]. In the present and other papers "formation" is defined as a paragenetic sedimentary and volcanic rock association that formed under similar tectonic, climatic and geochemical settings of the depositional medium. As an alternate definition, the formations may have been altered within narrowly defined limits. Each formation is considered a geological unit that marks a development stage in basic structural zones and includes a characteristic mineral resource complex [14].

The system of platform formations, quantitatively discussed in the present paper, follows legends that accompany various tectonic atlases [3-6]. They were used to measure formation volumes in the East European and Siberian Platforms. Additionally, atlases of the World's lithological formations [15, 16] were used in establishing formation volumes in other ancient continental platforms. Measurements of individual formations and their categories were summarized (Table 1). Eight classes have been established for these diverse formations on the basis of these characteristics:

(1) The continental terrigenous formation group includes red, variegated and gray beds of various composition, facies and climatic formation conditions. They contain mostly clayey, aleurolitic and sandy rocks, with minor amounts of secondary, accessory [23], minerals; conglomerates, marls, dolomites, gypsum, anhydrites, and other rocks. In the overall balance of the East European Platform, arid clayey deposits dominate over humid types.

(2) The glacial formation category includes the glacial cover (moraines), fluvioglacial (eskers, kames) and glacial-lacustrine deposits that consist almost exclusively of terrigenous matter (blocks, poorly sorted sandy-clayey deposits, varve clays). They formed at low and reduced temperatures. These deposits are relatively limited.

(3) The group of coal-bearing deposits includes limnic and paralic coal-bearing formations. Clayey and sandy deposits dominate, with coal beds that are always present. Limestone layers occur occasionally.

(4) The group of sandy-clayey marine formations includes formations, different in composition and depositional conditions. They formed during transgressive and regressive stages. Widespread in the East European and other ancient platforms.

(5) The group of carbonate units includes the arid subgroup. It is composed essentially of dolomites, and a humid subgroup that is composed basically of limestones. The arid dolomite unit occurs mostly in the central parts of ancient basins and is replaced in marginal zones by limestones. This resulted from the freshening effect of stream waters, discharged from tectonically active lands [12]. Inclusions and layers of gypsum and sandstones, also red and variegated marls, carbonate-rich clays and sandstones occur but do not exceed 10% of the total sediment volume. Humid climate limestone formations mostly include limestones or chalks, with quartz sand layers, kaolinitic clays and phosphorite concretions. Dolomites, gypsum, anhydrite and salts are practically absent. Terrigenous layers generally are free of carbonates.

(6) Salt- and gypsum-bearing units contain mostly rock salt, gypsum and anhydrite, less frequently K-salts. A significant number of dolomite layers occur along with sandstone-redbeds and clay rocks. This is a typically arid climate assemblage.

(7) Siliceous formation group includes Cretaceous, Paleocene, Eocene opokas, opokalike clays, tripolis, with chalk, marl, and limestones layers. Paleozoic siliceous shales occur among deposits of the ancient platforms. The sediment volume of this category is very small; less than a few tenths of one percent of the total sediment volume.

(8) Volcanic (trap) rock formations include tholeiitic basalts and trap (alkaline) basalt units that erupted mostly on continents.

The distribution of these platform units displays an evolutionary pattern through time as well as changes caused by tectonic cycles. Another project will deal with this particular topic. We investigate the mean distribution values of the formation volumes, weighed according to individual stratigraphic complexes in each platform, within separate time intervals, R-Q. Their distribution patterns between the Laurasian and the Gondwana Platforms have also been compared.

Quantitative relationships between units of the Russian Plate and its main structural zones are examined first (Table 3). The data show that more than half of the Plate's sediment cover consists of terrigenous formations (54.7% of the plate's total sediment volume). Marine sandy-clayey deposits are most widespread (34.5%), followed by the continental sandy-clayey (23.6%) and coal-bearing formations (2.0%), and bituminous shale units (1.3%). The distribution of glacial formations that blanket such areas could not be measured precisely. By a rough estimate, their concentration does not exceed 0.1%. Limestone formations (20.6%) dominate the carbonates. Dolomitic units (10.8%) are also important, while chalky units (1.9%) and associated siliceous deposits (0.2%) are less significant. Salt- and gypsum-bearing units are important (3.8%)*; while trap formations (1.3%) are insignificant in the Russian Plate. This indicates the modest contribution of volcanic matter to the cover units.

The concentration pattern of the lithologic units among the main structure categories of the Russian Plate is illustrated in Table 3. It shows that changes in the group ratios are directly related to tectonic conditions of sedimentation. In areas of relative uplift, in anteklise, massif and shield slope areas, their maximum contribution to the sediment cover is represented in the combination of terrigenous deposits (71.7%); in particular continental (35.4%), and marine (33.0%) sandy-clayey formations, while the bituminous shale content (0.9%) was reduced, as were the limey (18.3%) and dolomitic (7.7%) formations. Salt and gypsum-bearing units were practically absent. This structural type contained the best developed siliceous formations (0.8%). In the syneklise area, their concentration dropped to 0.1%; almost to zero in the graben-type basins. The proportion of sandy-clayey formations is reduced in the direction toward synecclises (19.4%), while that of the limey (27.4%), dolomitic (13.7%) and salt-bearing (3.4%) formations increases.

Formations in grabenlike basins developed under peculiar conditions. They differ from sediments in synecclises by the higher continental (30.3%) and marine (38.1%) sediment content and in the significant reduction in limey (10.2%) and dolomitic (4.0%) formation, in particular in Riphean and Lower Vendian aulacogens. At the same time, the proportions of salt-bearing (6.9%) and volcanogenic (4.5%) units increased.

The Russian Platform thus displays a strong quantitative relationship between continental deposits and certain structure types. Terrigenous deposits dominate (71.7%) in uplift zones (antecclises and others), while in belts of subsidence and burial (synecclises), their proportion is reduced (55.3%) and carbonate deposits (41.1%) become prominent. In contrast, uplift zones contain only 27.0% carbonate units. Aulacogens include maximum of total terrigenous matter (74.4%); also evaporites (6.9%) and trap (4.5%) formations and a minimum of carbonate units (14.2%).** The presence of trap formations in the aulacogen conforms with the occurrence of deep faults that surround these structures. The similarity in the distribution patter of the formation group is greatest between the East European and North American Platforms (Table 1). The proportion of terrigenous formations in the sedimentary platform covers is quite similar (54.7%, correspondingly, 61.6%). The carbonate formation content is also similar (36.1% vs 33.6%). However, differences also exist between the two platforms. Continental sandy-clayey formations are less abundant in the North American Platform than in the East European (10.8% vs 21.3%) and the marine clayey-sandy group is developed best (48.6% vs 31.6%). In addition, the East European Platform contains more than twice the salt-bearing formations (8.2%) of the North American Platform (2.7%). Trap formations are more widespread in North America (2.1% vs 0.9%) Quantitatively, the Chinese Platform shares quantitative similarities with these two (Table 1). To an extent greater than other Laurasian platforms, the Siberian Platform differs from the East European in ratios of formation types in the sediment cover (Table 1). Terrigenous deposits are the least developed; their ratios are significantly smaller than in the East European, Chinese, and North American Platforms. This fact is reflected by the reduced continental sand-clay content; less than half of those of the East

*When the East European Platform is considered as a whole, including also the upper, measurable marginal syneklise horizons of the plate, this value is doubled. The procedure would primarily involve the Precaspian Syneklise.

**Terrigenous deposits dominate in the Upper Proterozoic aulacogen deposits, while the carbonate and, especially, the evaporite formation content is greatly diminished.

European Platform and Chinese Platforms. Carbonate, coal- and salt-bearing formations are more widespread in the Siberian Platform. The salt content in the Platform equals that of the East European Platform value. It is twice as great as in the North American Platform. It is 24 times the concentration of the Chinese Platform. Among the ancient Laurasian platforms and globally, the Siberian Platform has the highest coal and salt concentration values.

In terms of its rock composition (Table 1), the East European Platform differs radically from the Gondwana Platform. It contains fewer terrigenous and volcanogenic formations and a much greater proportion of carbonate and salt formations. These resemble ratios of the mean total Laurasian Platform values (Fig. 5).

Comparison of data indicates a gradual reduction in the ratio of terrigenous formations and a corresponding increase in the total carbonate content in a number of individual Gondwana and Laurasian platforms (Fig. 6a).

An attempt is made to explain this phenomenon. It would be natural to expect a direct relationship between the distribution of terrigenous formations and the cratonization coefficients in the ancient platforms. This shows a connection between the stable crustal uplift areas (shields) and areas of subsidence and burial (plates and marginal synclises). This assumption generally is supported by data (Fig. 6b) that suggest that reduction in the total terrigenous rock volume is accompanied by reduction in cratonization coefficient values when these parameters are compared between all Gondwana and all Laurasian platforms. However, on a global scale (Fig. 6b) individual ancient platforms, including those of Gondwana and Laurasia (Fig. 6a), reveal a significant deviation of the K_{cr} -curve from the curve that reflects the entire pattern of volume distribution of the terrigenous formations. There is also a tendency toward reduction of the cratonization index in the sequence. Intervening peaks and lows complicate this trend. Deviations from the curve occurred in individual platforms, not only with relationship to shields and plates, but also as the result of many other factors, including shield uplift rates and interior uplift in plates. The uplift rates controlled rock erosion intensities in the source regions. Climatic conditions of weathering were also most important. These conditions changed in time and differed from platform-to-platform. Quantitative evaluation of the impact by these factors is the task of future studies.

There is also a trend in areas of ancient platforms toward an increase in distribution areas of terrigenous beds and a reduction of carbonate deposition areas with increasing rates of burial under accumulating sediments. This is shown clearly only on a global scale if these parameters are compared within areas of large crustal blocks, such as the combined Gondwana and combined Laurasian Platforms (Fig. 6b). During the review of only individual platforms, this relationship practically disappears (Fig. 6a). Distribution patterns of carbonate formations in individual platforms were determined not only by subsidence rates in a depositional area but were influenced also by many other factors, such as basin size, basin water salinity, climatic conditions during deposition, etc. Very detailed and differentiated quantitative analyses that cover various time units would be needed to solve this problem.

Our comparative analysis of quantitative parameters of the largest ancient platforms worldwide and distribution of the associated three lithologic formation groups leads us to regard the East European Platform not only as the "tectonotype," but also as the "lithotype" of ancient platforms. However, the lithotype designation applies only to Laurasian continents. The lesser development of marine sandy-clayey deposits, the significantly greater concentrations of evaporites and very poor development of continental volcanic formations, in comparison with mean values of all ancient platforms worldwide sharply distinguishes the East European Platform from the Gondwana platform group. The African or Hindustan Platforms represent the "tectonotype" and "lithotype" of Gondwana platforms correctly.

LITERATURE CITED

1. Atlas of Lithological-Paleogeographic Charts of the Russian Platform and Its Geosynclinal Framework, Vol. 1, Upper Precambrian and Paleozoic [in Russian], Gosgeoltekhizdat, Leningrad-Moscow (1981).
2. Atlas of Lithological-Paleogeographic Charts of the Russian Platform and Its Geosynclinal Framework, Vol. 2, Mesozoic and Cenozoic [in Russian], Gosgeoltekhizdat, Leningrad-Moscow (1962).
3. Atlas of Lithological-Paleogeographic Charts of the USSR, Vol. 1 (Precambrian, Cambrian, Ordovician, Silurian) [in Russian], Ministry of Geology USSR, Moscow (1968).
4. Atlas of Lithological-Paleogeographic Charts of the USSR, Vol. 2 (Devonian, Carboniferous, Permian) [in Russian], All-Union Aerogeological Trust, Ministry of Geology, Moscow (1969).
5. Atlas of Lithological-Paleogeographic Charts of the USSR, Vol. 3 (Triassic, Jurassic, Cretaceous) [in Russian], Ministry of Geology of the USSR, Moscow (1969).

6. Atlas of Lithological-Paleogeographic Charts of the USSR, Vol. 4 (Paleogene, Neogene, Quaternary Period) [in Russian], Ministry of Geology of the USSR, Moscow (1967).
7. V. V. Belousov, Basic Problems of Geotectonics [in Russian], Geogeoltekhizdat, Moscow (1962).
8. A. A. Bogdanov, "General problems of the tectonics of ancient platforms; the East European Platform," Sov. Geol., No. 9, 3-26 (1964).
9. L. E. Levin, Tectonic Map of the Skifsk and Mizinsk Platforms [in Russian], Ministry of Geology of the USSR, Moscow (1970).
10. N. S. Shatskii (ed.), International Geological Atlas of Europe, Scale: 1:25 million, International Geological Congress, Gosgeoltekhizdat, Moscow (1962).
11. V. I. Popov, Classification and Description of Geological Formations [in Russian], Nedra, Leningrad (1968).
12. A. B. Ronov, "Chemical composition and formation conditions of Paleozoic carbonate units of the Russian Platform, based on lithological-geochemical charts," Trudy GIN, Academy of Sciences, USSR, No. 4, 256-343 (1956).
13. A. B. Ronov, A. M. Migdisov, and V. E. Khain, "Potentials and limitations of the volume method: example of the Russian platform and surrounding deep basins," Litol. Polezn. Iskop., No. 4, 3-14 (1973).
14. A. B. Ronov and V. E. Khain, "Devonian lithologic formations worldwide," Sov. Geol., No. 41, 47-76 (1954).
15. A. B. Ronov, V. E. Khain, and K. B. Seslavinskii, Atlas of Lithological-Paleogeographic Charts of the World, Late Precambrian and Paleozoic of the Continents [in Russian], Nauka, Moscow (1984).
16. A. B. Ronov, V. E. Khain, and A. N. Balukhovskii, Atlas of Lithologic-Paleogeographic Charts of the World (Mesozoic and Cenozoic of Continents and Oceans) [in Russian], Izd-vo Akad. Nauk SSSR, Leningrad (1989).
17. A. B. Ronov, A. A. Yaroshevskii, and A. A. Migdisov, Chemical Composition of the Earth's Crust and Geochemical Balance of the Main Elements [in Russian], Nauka, Moscow (1990).
18. L. B. Rukhin, Introduction to Lithology [in Russian], Gostoptekhizdat, Moscow—Leningrad (1953).
19. N. M. Strakhov, Introduction to the Theory of Lithogenesis [in Russian] (1960-1962).
20. L. N. Rozanov (ed.), Tectonic Chart of Hydrocarbon-Bearing Regions of the USSR [in Russian], Scale: 1:25 million, All-Union Aerogeological Trust, Ministry of Geology of the USSR (1970).
21. N. S. Shatskii, "Parageneses of sedimentary and volcanic rocks and formations," Izv. Akad. Nauk SSSR, Ser. Geol., No. 5, 3-24 (1960).
22. Physical Geographic Atlas of the World, Geodetic and Cartographic Main Administration of the GGK, USSR [in Russian], Moscow (1964).
23. V. E. Khain, General Geotectonics [in Russian], Nedra, Moscow (1973).
24. N. P. Kheraskov, Tectonics and Formations [in Russian], Nauka, Moscow (1967).
25. A. L. Yashin, Principles in Establishing Geological Formations. Introduction to the Work, "Pre-Mesozoic Redbed Formations" [in Russian], A. I. Anatol'eva, Nauka, Novosibirsk (1972).
26. P. B. King, Tectonic Map of North America, Scale: 1:5 million, U.S. Geological Survey Professional Paper, Washington D.C. B-28 (1969);
27. W. Pozarjski, "Powierzchnia skonsolidowanego podloza," Geofizyka i Geologiya Naftowa, No. 3-4, Pt. 1 (1970).

THE MANGANESE ORES OF RUSSIA*

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The current state of the manganese reserve base in Russia has been characterized. A thesis is laid out which indicates that the discovery of manganese ores in Russia whose quality equals that of countries which export manganese ores is unlikely. The necessity to concentrate efforts on the evaluation of the Mesozoic–Kainozoic oxidation zones of manganese formations is shown. These formations often contain small ore bodies made up of easily upgraded manganite–pyrolusite–psilomelane oxides. A table giving possible future manganese ore resources in Russia is given.

In the territories of the former SSSR manganese ores are only mined in the Ukraine, Georgia, and Kazakhstan. The concentrates obtained from these ores meet international technical standards.

Because of the break-up of the SSSR the metallurgical industry of Russia, which is one of the main users of manganese, must either import raw material on the international market, or make use of its own reserves. Both of these approaches will lead to an increase in the final product cost.

The annual production of manganese ore in the SSSR was about 20 million tons at a cost of 40-60 rubles per ton (January 1, 1991). In the same year 12 million tons of manganese ore was produced at a cost of 170-200 dollars per ton outside the USSR. Such a large difference in price without a significant difference in the quality of our ores (Table 1) was due to the governmental monopoly of the economy in the SSSR, and, mainly, by low labor costs.

The manganese ore base of Russia began to develop in the early periods of World War II when the Southern Ukrainian (Nikopol) manganese ore base was occupied by the Germans, the Western Georgia (Chiatury) base was practically cut off from metallurgical centers, and the central Kazakhstanian (Karazhal, Ushkatyn, etc.) bases were still not known. After the defeat of the Germans the former economic ties were reestablished, and the exploitation of the Russian deposits was gradually phased out. The mining of manganese ore continued (up to 1965) at the deposits of the Northern Ural manganese ore basin of the Paleozoic age [9].

Practically all of the deposits exploited in Russia consist of low quality primary ore, and are not large [1, 3-6, 8]. Their oxidation (manganese and caps) zones were advantageously developed, and it was here that small bodies (lens) of oxidized ore consisting of pyrolusite–psilomelane are located. Thus, practically all of the oxide (oxidized) ores of the Sapal'sk deposit in the central Urals, and the Durnovsk and Mazul'sk deposits in southern Siberia, and others have been worked out.

The search for manganese ores in Russia did not end after the return to imports from Nikopol' and Chiatury. Intensive exploratory work continued after the war by many PGO MinGeo of the SSSR, but a significant change from using the known deposits in the Ukraine, Georgia, and in Kazakhstan did not occur.

The results of this work were summarized at the VSEGEI on a map which showed the territories in the SSSR where manganese ores could possibly be found on a scale of 1:7,500,000 (Fig. 1). In representing the manganese ores on the map, we have included any rock which contains more than 10-15% manganese oxide, carbonate, or silicate in its mineralogical composition. And even at such a low level of manganese in the ores, which is far below economic feasibility for use in metallurgy, the total amount of reserves in Russia has been estimated at about 0.5 billion MT.

In the following years geological studies gave an estimate (mainly negative) of the majority of the perspective areas shown on the map including, for example, Kureisk, Sakhalinsk, Zabaikal'sk, etc. At the same time new areas were presented, and the perspectives of the already known were further delineated. On the mineral-genesis map of the SSSR

*Results from the Interdepartmental Conference "Real Problems concerning the Formation, Prediction, and Exploration of Manganese Ores." Saint Petersburg, VSEGEI, September 29-October 1, 1992 [6].

TABLE 1. Characteristics of Manganese Ore Reserves

Exporting countries and deposits in the former SSSR	Remaining confirmed reserves, in millions of MT	Mn, %	Main component of the ore
Australia	200	25-50	Mn hydroxides
Brazil	200	40-53	"
Gabon	200	48-60	"
India	100	25-62*	Mn hydroxides and oxides
South Africa	1000	20-44	Mn hydroxides
Southern Ukrainian Basin	{ 400	28 †	"
Nikopol'skoe Deposit	{ 350	23	Mn carbonates
Bol'shoi Tokmak	1500	21	"
Western Georgian Basin (Chiatyry)	{ 60	26	Mn hydroxides
	{ 140	18	Mn carbonates
Central Kazakhstan Basin (Karazhal, Ushkatyn)	85	22	Mn hydroxides and oxides
	280	20	Mn carbonates, oxides, and silicates
Northern Ural Basin	40	20-22	Mn carbonates
Usinskoe Deposit	98	19-20	

*Exported Ore - >55% MnO.

†"Washed" Ore (for trade) - 32-44% Mn concentrate.

shown at a scale of 1:5,000,000 [2] it can be seen that perspective areas are only to be found in the Urals, the Eniseisk Block, the Far East, and in the Altae Sayansk region.

In following MinGeos of the USSR estimates of the manganese reserves were made in 1983 and 1989.

In 1983 reserves in the RSFSR were estimated at 1.5 billion MT (which includes 50 million MT of oxides). The main bulk of the reserves (1 billion MT) are composed of the oxide-carbonate and carbonate ores of the Southern Island of Novaya Zemlya (500 million MT) and of the Peshsk Depression (North Timansk Block - 500 MT).

The Manganese Ores of Novoya Zemlya

The wide distribution of the manganese containing minerals among the Lower Permian deposits of Novoya Zemlya and Pai-Hoi was established at the end of the 1970's and the beginning of the 1980's [3] (see Fig. 1). The most interest, according to its discoverers, belongs to the Rogachevsk-Taininsk area which is located in the central part of the southern island. The productive flysch-like strata having a thickness of 50 (in the southeastern section) to 130 m (in the northern section) consists of interstratified argillite blocks with layers containing varying amounts of rhodochrosite-silicate ores. The size of the latter range from 2 to 25 cm, and the saturation of the separate argillite blocks with the ore layers ranges from 10 to 80%. The ores are crypto- and micrograin sized and intermixed with manganese carbonates and quartz.

In reports given at a conference (V. Kh. Nasedkina, L. G. Pavlov, Yu. D. Shul'ga, I. K. Ermolaev, V. I. Ustritskii, and L. G. Povysheva) a very objective characterization of both the ore composition and distribution were outlined. From these materials, and also from the publications of other investigators, it can be seen that there existed an abundant closed basin which is part of the Ural geosyncline in the islands of the Novoya Zemlya and Pai Hoi regions in the early Permian. The accumulation of manganese carbonates took place over an area of about ten thousand square kilometers. However, this occurred during a tectonic stress cycle and was accompanied by the addition of a large amount of terrigenous material. In this context, the mean concentration of manganese (in the rhodochrosite and manganocalcite) in the most promising block was 15-20% with P_2O_5 at 0.1-0.2%, and with a silicate modulus of $SiO_2/Mn > 3$.

One can see that there is an uneven dissemination of sphalerite, chalcopryrite, pyrite, alabandite, and also an increased concentration of zinc, nickel, barium, cobalt, copper, and chromium carbonates. There is no other place in the world where such a category of manganese ores exists. In Table 2 they are listed as "Potential Mineral Reserve."*

*Potential Mineral Reserve - The amount of rock containing useful components whose form or occurrence do not currently permit it to be economically recovered but may in the near future.

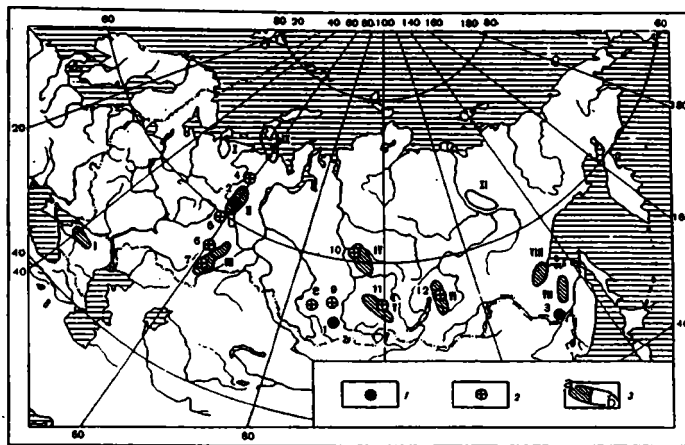


Fig. 1. The distribution of possible manganese ore reserves in Russia. 1) Deposits included in the reserve balance (1 – Usinsk, 2 – Northern Ural Group, 3 – Khingansk Group); 2) Deposits not included in the reserve balance (4 – Parnoksk, 5 – Sapal'sk, 6 – Ulutelyak, 7 – Akkermanovsk, 8 – Durnovsk, 9 – Mazul'sk, 10 – Porozhinsk, 11 – Nikolaevsk, 12 – Oldakitsk); 3) Manganese enriched regions (a – possible reserves: I – North Kavkazsk, II – North Ural, III – South Ural, IV – Eniseisk, V – Prisayansk, VI – Pre-Baltic, VII – Vandansk, VIII – Udsko-Shantarsk; b – with metallogenic potential: IX – Pai-Hoi Novozemel'sk, X – Peshsk, XI – Yakutsk).

Processes for the hypergenic formation of manganoous rocks in the arctic climatic conditions of Novoya Zemlya are very limited. In addition, the islands of Novoya Zemlya underwent intensive erosion and glacial wear over a long period of time. And although there are known manganese oxides ores associated with fissures and cracks in the locked sections of folds, little is known about them. The concentration of manganese, mainly present in cryptomelane and pyrolusite and obtained from separate drill samples, was 15-20%. The predicted reserves do not exceed several ten thousand MT. The hypergenic ores are characterized by an increased concentration of phosphorous, zinc, strontium, barium, copper, nickel, and cobalt.

The Manganese Ores of Northern Pritiman'e

In the beginning of the 1980's nodular limonite containing 16% manganese dioxide was discovered by V. A. Piven working for the VSEGEI in the north in the Timansk ridge. This ridge is in the Peshsk depression in the Prishchatinita clefts where the basalt horizontals of the Lower Jura are revealed. Similar nodules are rarely found in the basalt horizontals of the Jura and in other regions of Russia, in particular in Yakuti, Central Russia, and in other areas. The find in the Peshsk depression served as a basis for further exploratory drilling. Among the sandstone and clay deposits at a depth of 100 m and more, small layers of manganese enriched siltstone (5-20% Mn) were encountered in the lower Jura fissure. The manganese was in the form of carbonates and supposedly in the form of hydrosilicates. Economical ore finds have not yet been discovered, although exploration is continuing.

Ural

In the Urals forecasts have only been given on the carbonate ores of Bashkiri (Ulutelyaksk deposit). In the region of the deposit large lower Permian gypsum–anhydride strata have developed. Here layers of manganese limestones containing up to 5-10% Mn as manganese calcites and manganese dolomites are intersected by occasional gaps. Recently, Ulutelyak has been described as a deposit, not of manganese ores, but of manganese limestones. In terms of their genesis and growth the following point of view exists which is in sharp contrast to that found in the literature.

The gypsum–anhydride stratum at the surface underwent intensive hypergenic transformation during the Paleocene in the presence of water and petroleum (the deposit is located near petroleum reservoirs). As a result, carbonates were formed in areas of 5-10 m. Under these conditions desulfurization of the gypsum and of the anhydrides occurred, not

TABLE 2. Potential Manganese Ore Reserves in Russia

Region	Ore characteristics	Age index	Predicted reserves, million MT	Potential mineral reserves, million MT
Ural Mobile Belt				
Southern Ural	1. Volcanic—Siliceous Formation (Karagalinsk, Kos-Istevsk, Rakhmetovsk and other deposits). Fine lenticularlike layers of hausmannite-braunite-rhodonite silicate ores among jasperite which has been interlayered with basalts, porphyrites, and their tufas. Mn 15-25%, SiO ₂ 30-50%.	S—D ₂	—	50-100
	2. Silicate—Carbonate Formations (Akkermanovsk, Kipchaksk and other deposits). Lenticularlike stratum of silicate—carbonate mainly manganocalcite ore. Mn 15-20%. Quartz and chalcedony in intimate intergrowth with manganese carbonate. Occasionally with increased concentrations of Pb and Zn.		50	200
	3. Gypsum—Lime Formations (Ulutelyaksk deposit). Layers of flux limes with manganocalcite and manganodolomite 2-4 m in size among gypsum—anhydrite strata. Mn 5-10%, SiO ₂ 8-12%, P ₂ O ₅ 0.5-0.8%.		100	100
	4. Weathered Crust Formations (Akkermanovsk, Ulutelyaksk and other deposits). Ore caps of the usually linear type including layers and lens of pyrolusite—psilomelane ores often containing silica and goethite. Mn 25-45%, SiO ₂ up to 40%.	K ₂ —P ₃	10-15	—
Central Ural	1. Volcanic—Carbonate Metasomatic Formations (Sapal'sk and other deposits of the Vysokogorsk region). Carbonate ores (Small plates and lens): Mn 15-30%, SiO ₂ 3-8%, P ₂ O ₅ 0.03-0.08%, Pb up to 2% and Ln up to 1%.	S ₂ —D ₁	10	—
	Braunite—hausmannite oxides and pyrolusite—psilomelane hydroxide ores, 40-50%.	D ₁ —KZ	The latter practically worked out	—
	2. Silicate—Carbonate Formations (Klevakensk and other deposits). The ore parameters are the same as similar ore types in the southern Urals	D ₃ —C ₁	20	100
	3. Weathered Crust Formations . Ore caps that are similar to the caps of the southern Urals but having undergone intense erosion in the KZ.	K ₂ —P ₃	2-5	—
Northern and Polar Ural	1. Volcanic—Silicate—Carbonate Formations (Parnoksk deposits). Low phosphorous (hundredths of a percent) carbonate ores, Mn 20-30%. Silicate modulus > 1.	O ₂	100	200 (including silicate ores)
	2. Weathered Crust Formations (Parnoksk and other deposits). Linear zones of manganese usually containing carbonate rocks appearing with the emergence of the MZ—KZ surface. Lenticularlike bodies of lightly enriched pyrolusite—psilomelane ores Mn 20-40%.	K ₂ —P	5-10	—
Southern Island of Novaya Zemlya	1. Carbonate—Terrigenous Formations . Silicate—rhodochrosite ores interlayered with schists and siltstones. Mn 10-20%, P ₂ O ₅ 0.1%, Silicate modulus > 2.5.	P ₁	—	Billion MT

TABLE 2 (continued)

Region	Ore characteristics	Age index	Predicted reserves, million MT	Potential mineral reserves, million MT
Siberia				
Eniseisk Ridge	1. Volcanic-Terrigenous Formations. Silicate-rhodochrosite, dolomite-rhodochrosite ores. Mn 8-15%. Silicate modulus >2.5.	PR ₂	—	Hundreds of millions MT
	2. Weathered Crust Formations (Porozhininsk group of deposits). Manganite-psilomelane ores in cave depressions which have developed on manganic silicate-carbonate rocks. Mn 20-30%. Silicate modulus >2.		30	40
Altai-Sayansk Region	1. Tufogenic-Silicate-Carbonate Group of Formations. Essentially carbonate rocks containing a low concentration of Mn and with a high silicate modulus.	PR ₂	—	Hundreds of millions MT
	2. Weathered Crust Formations (Nikolavsk, Oldakit'sk and other deposits). Pyrolusite-psilomelane ores in manganous caps over low-grade carbonate ores. Mn 20-40%.	K ₂ -P	20	—
Far East				
Udsk-Shantarsk Zone	1. Volcanic-Silicate Formations (Iryungdinsk deposits and others). Iron-manganese essentially braunite-hematite ores Mn 10-20%, Fe 25-35%.	C	20	50
Malyi Khingan	1. Volcanic-Silicate Metamorphic Formations. Oxide and oxide and oxide-silicate difficult to enrich ores. Mn 15-20%.	PR ₁	20	—
Northern Pritiman'e	Sand and Clay Formations (Ore sandstone developments). Carbonate and Hydrosilicate ores. Mn 15-20%. Silicate modulus >2.	J ₁	—	100

only in the subsurface zone, but also penetrated into deeper drainage zones. Together with the synthesis of calcite in these zones, there was movement of bivalent manganese compounds which had entered into the carbonate composition. Later, an ore cap formed in the upper regions of the manganese areas composed primarily of the manganese hydroxides vernadite and psilomelane. The concentration of manganese in the ore rock of the cap is up to 35%. They can be considered to be a manganese ore [7].

As early as 1942 pilot plant tests were carried out on the manganese limestones of Ulutelyak. According to D. D. Budakov and V. I. Sysoev, "Ferromanganese obtained from the smelting of current ore grades can be almost completely replaced by those obtained from manganese limestones." [10, p. 84].

In 1989 the predicted reserves of the PSFSR excluded those found in Novaya Zemlya, and the reserves in the Peshskoi depression were 4 times less. On the other hand, the reserves in Siberia and in the Far East were greatly expanded, mainly those of two new and large manganese deposits with reserves which exceed the proven reserves of such large manganese exporting countries as India/Gabon, etc. These manganese deposits are in the western slope of the subpolar Urals (Parnok region with about 0.5 billion MT) and in Yakuti (150 million MT). The net effect was that the predicted reserves of manganese ore in Russia in 1989 showed little change and was about 1.5 billion MT.

What exactly is to be made of the new (1989) predicted reserves found in the study by the Mingeev SSSR?

The Ordovician basin of the Subpolar Ural (Komi SSR, Fe-Mn deposits of Parnok, etc.) has been studied by a number of investigators (V. Kh. Nasedkina, I. D. Konyaeva, E. G. Ozhogina, A. A. Bulkin, M. A. Shishkin, N. N. Gerasimov, and S. A. Onishchenko).

The Parnok deposit is attached to the silicate-carbonate formation of the middle Ordovician. It is composed of irregularly alternating lenticular strata of manganese and iron ores which are interlaced with manganese limestones and siltstone. Carbonates, carbonate-silicates and silicate ores predominate in the deposit. The investigators have noted that the ores contain low quantities of phosphorous (0.005-0.003% for each 1% of Mn) and have a mean Mn concentration of 25-30%.

In our opinion, at this time only the oxides, essentially the cryptomelane and psilomelane ores, are of sufficient quality to be used to produce peroxide concentrates. These ores compose small lens in the linear zones of the MZ-KZ hypergenesis.

The predicted reserves of oxide ores in Parnok are a few million MT, and, in our opinion, the total reserve over the whole basin is about no more than 10 million MT.

Vilyuiskaya Syncline (Yakutskaya-Sakha SSR)

In the basalt horizontals of the Jura, which includes the Vilyuiskaya syncline in the so-called variegated blocks of the lower Jura, nodules of manganese containing limonite have been reported. The manganese concentration usually exceeds that of the percent abundance in the earth, and in separate locations achieves levels of 3% at an iron concentration of 10-20% (Report of V. K. Maslov and V. G. Okorokov). Despite special studies, neither manganese nor iron ores have been discovered in the Vilyuiskoi syncline. Only separate mineralization areas were noted during a geological survey carried out in the Jura and in the Paleocene basin of the Lena river. In this context, not only is there no basis for considering the presence of predicted reserves, but there is also no basis for carrying out a determination of the manganese potential in the Vilyuiskaya syncline.

Manganese ores of the upper Proterozoic containing up to 5-9% Mn have recently been encountered in the middle region of the Lena river on the eastern border of the syncline. Unfortunately, its oxidation zone is very insignificant which discounts it as a viable industrial deposit.

The predicted reserves of other regions in Russia, which have been characterized in conference reports, do not provide a basis for the discovery of deposits similar to those, not only found in exporting countries, but also those in the republics of the former SSSR.

Eniseiskii Ridge

Manganese deposits in the Eniseiskii Ridge are of the upper Proterozoic. The highest concentration of manganese is found in the northwestern limits of the Vorogovsk depression. Here there are blocks of volcanic-sedimentary rocks in a raised formation. The latter is composed of silicate and manganese tufa, dolomites, and layers of silicate-rhodochrosite and manganese-dolomite rock. The concentration of manganese is about 5-8% and in samples achieved levels of 30%. In itself the pre-Cambrian mineralization is not of industrial interest, but, falling into a hypergenic zone, it provokes the formation of industrial level deposits of oxide ores. It was just these ores that the reports of R. A. Tsykin, L. I. Sviridov, and L. P. Kostenko discuss.

The first discoveries of psilomelane-manganese oxide ores in the northwestern part of the Eniseisk ridge, which belong to the surface rock of the upper Proterozoic, were made in the 1970's. These discoveries formed the basis for predicting the further discovery of huge deposits of high quality manganese oxide ores in amounts reaching more than several hundred million MT. The initial drilling showed that the depths did not fit the extrapolation. It turned out that the industrial grade ore was only found in small lenticular bodies which were localized exclusively in the MZ-KZ hypergenic zones. The total predicted reserves probably do not exceed 100-150 million MT of manganite-psilomelane ore containing 20-30% manganese. Together with sediments, the deposits in the Eniseisk ridge contain infiltration ores. Thus, according to the findings of R. A. Tsykin et al. on the Mokhovoe deposit "the main ore mass consists of clays which have been intensively penetrated by manganese carbonates and oxides" [6, p. 90]. Similar hypergenic ores are characterized by a high concentration of phosphorus and of a high silicate modulus.

All along the southern framework of the West Siberian and Siberian plate a large amount of manganese ore deposits are known to exist. Exploratory work on the manganese in this area has been carried out over many years and by various geological organizations. Unfortunately, however, large industrial grade ore deposits have as yet not been found. Several of the known deposits (Durnovsk, Mazul'sk) were exploited during the war. The Usensk deposit was explored in the 1950's and currently, irregardless of the low quality of the ore, it is being prepared for exploitation.

The manganese value of this abundant region has been reported by E. G. Kassandrov, N. S. Lidin, E. V. Kassandrova, A. V. Tatarinov, V. I. Sizykh, and A. M. Mazukabazov. The majority of the manganese deposits belong to the structures of the geosyncline stages of territorial development and to activation zones. Often they are grouped near large fissures and contortion zones, and localized in tufogenic-silicate-carbonate formations of the upper Proterozoic-Cambrian. Carbonates predominate and to a much lesser extent oxide-carbonate ores. The manganese concentration is usually low (10-20%) with high values of the silicate modulus and concentrations of P_2O_5 more than 0.3-0.5%. The predicted reserves of these ores is estimated over a wide range: from a few thousand up to millions of MT depending not only on the volume of actual material, but also on the temperament of the investigator.

Far East

The far east region is currently not under consideration as a viable solution to the manganese ore problem of Russia. And not only for the reason that it is located thousands of continental kilometers from the metallurgical centers of the country. It is basically a young land that has undergone little intensive chemical weathering. This lowers the chances of finding rich oxide ores. The Malokhingansk group of fine deposits in the Evreisk autonomous regions contains silicate, hausmannite, and rhodochrosite ores with hematite and magnetite. Clearly defined and perspective deposits are only in the Vandansk range where KZ zones of oxidation have recently been found at outcroppings of manganese silicate-carbonates in Permian schists.

An analysis of the materials given in reports and published in recent years and partially presented here in Tables 1 and 2 indicates that there is a lack of perspective manganese deposits whose quality equals that of ores found in Austria, Brazil, Gabon, India, and South Africa.

Two paths are now open to the Russian metallurgical industry: 1) begin to use imported (both near and far foreign sources) raw material; 2) create our own raw material base using deposits within the country.

In terms of former economic ties in the SSSR, the best raw material was delivered to our factories from Ukraine, Georgia, and, recently, from Kazakhstan. But the political instability of the republics arising on the outskirts of the SSSR makes such an approach unreliable. Current projects aimed at constructing factories in Russia for the production of manganese dioxide from internal sources of raw material require large capital investments. In addition, enrichment of the low quality ores, no matter how effective it turned out to be, would not be competitive with the natural "free of charge" enrichments which have occurred in neighboring territories.

Before the conference sponsored by the Russian Geolkom was the problem of recommending the most rational means of creating a Russian manganese ore base. In doing so it was required that the raw material sources be located as close as possible to the main metallurgical centers of the country (South and Central Urals, Central Russia, and Kuzbass). Their conclusions were based on the following premises:

1. The highest quality and economical manganese deposits were formed in the hot and humid climates of the tropical Cenozoic zones of the earth where laterites are currently found.
2. The territories of Russia were out of the hot and humid climates as early as the end of the Mesozoic and therefore are free of such deposits. In Russia there are the less intensely weathered transformations of the crust which have occurred in an another (more ancient) age. There are also the narrow linear Kainozoic manganese carbonate oxidation zones.
3. Out of the various eras of hot and humid crust transformation, the most productive for Russia was the late Cretaceous, and, in places, extending into the Paleozoic. This era appeared mostly in the Urals in the Eniseisk ridge and along the southern framework of Siberia. Unfortunately, the Kainozoic tectonomagmatic activation, accompanied by

reconstruction of the plan and relief of these regions, led to the destruction of the weathered Cretaceous surface, degradation of the weathered crust, and partial destruction of the hypergenic manganese deposits which were attached to these areas. These activities have made it practically impossible to find large manganese ore deposits.

4. Thus, the problem of predicting and finding manganese ores in Russia, in our opinion, should not concentrate on accumulating reserves containing 15-20% manganese as carbonates, which do not compare to manganese ores used around the world and which has been done up until now, but should concentrate on the discovery of oxide (oxidized) ore deposits. These deposits are usually localized in oxidation zones of carbonate, carbonate-silicate, and volcanogenic-silicate manganese formations. The ores belong either to hypergenic zones (weathered crust and other formations), or, as proposed by A. V. Tatarinov and others [6], arise in association with tectonomagmatic activations. In any case, the reserve base of oxide ores in deposits of such type will not exceed several million MT. However, since they lie close to the surface, they are economically exploitable. An example might be the Kainozoic Nikolaevsk deposit which belongs to an oxidation zone in a stratum of ancient manganese carbonate rock. The deposit lies in the foot hills of Sayan (40 km southwest of Nizhneudinsk), and is currently be exploited by small companies. The ores contain 40-50% manganese and are easily enriched. The local battery factory is buying concentrate for 9000-16,000 rubles per MT.

The most perspective areas for the discovery of similar deposits are the following:

1. In the southern Urals and in Mugodzhär, both within the limits of the Magnitogorsk syncline and in its western slopes along the outcroppings of manganese carbonate-terrogenesis formations.
2. In the middle Urals in the Tagilo-Magnitogorsk syncline where local residual mountains of the weathered Cretaceous surface remain and have developed into the potential manganese deposits of the lower and middle Paleozoic.
3. In the Altae-Sayansk region it would be advantageous to carry out a review of all of the various manganese minerals in the ancient (PR-E) strata in order to isolate areas which would likely lead to the discovery of MZ-KZ oxidation zones. In this context, special attention should be given to the residual mountains of the Cretaceous-Paleocene weathered surface which have been covered by the N-Q mantle.

LITERATURE CITED

1. A. G. Betekhtin, Industrial Manganese Ores [in Russian], Izd-vo AN SSSR, Moscow-Leningrad (1946).
2. B. M. Mikhailov (ed.), Mineralization Map of the SSSR at a Scale of 1:5,000,000 on 4 Pages with Notes [in Russian], VSEGEI, Leningrad (1989).
3. Manganese Ore Formation in the SSSR [in Russian], Nauka, Moscow (1984).
4. Manganese Deposits of the SSSR [in Russian], Nauka, Moscow (1967).
5. Manganese Deposits in the Folded Regions of the SSSR [in Russian], Nauka, Moscow (1978).
6. Manganese Ores. Reports of the Interdepartmental Conference "Real Problems in the Formation and Discovery of Manganese Ores" [in Russian], Saint Petersburg (1992).
7. B. M. Mikhailov, V. G. Kolokol'tsev, and Yu. M. Vorob'ev "Manganese ores in the weathered crust of the southern Urals and Kazakhstan," in: Problems of Ore Formation, IV Symposium IAGOD, Vol. III (1974), pp. 82-89.
8. B. M. Mikhailov and V. S. Rogov, "Geological premises for predicted the location of manganese deposits in the Urals," Sov. Geol., No. 8, 24-31 (1985).
9. S. D. Rabinovich, The Northern Urals Manganese Ore Base [in Russian], Nedra, Moscow (1971).
10. A. V. Khabakov, "Ulu-Telyak, a new oxidized manganese carbonate deposits in the Permian sediments of Bashkir (Western Slope of the Southern Urals)," Izv. Akad. Nauk SSSR, Geol. Ser., No. 4, 70-85 (1944).

TRIASSIC – JURASSIC BAUXITES OF SYRIA

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Newly discovered deposits of boemitic bauxite on the Arabian platform are described. They are located in the Palmyra Mountains in Syria, and are dated latest Triassic to early – middle Jurassic. The structure, composition, and facies of these sedimentary karst bauxites were studied. Evidence of secondary alteration was found (diagenetic, epigenetic, and low-temperature hydrothermal). These ores were clearly developed along the southern, northern, and western margins of Mesotethys during the Triassic – Jurassic bauxite-forming epoch.

Thick, humid Triassic–Jurassic weathered rock and the products of its erosion along with bauxites* are known around the world, at various latitudes from the Polar Urals to the tropics of the Hindustan peninsula, and in various tectonic settings: fold belts (Mediterranean) and platforms both ancient (Siberia, Hindustan) and young (Turan and Skopje plates). Weathered rocks and bauxites of the Laurentian platform are fully described in the literature. Much less has been written about the Triassic–Jurassic weathering mantle and bauxites of the Gondwana platform, which include the bauxites of Syria and Israel in the northwestern Arabian peninsula.

Lower Mesozoic lateritic karst bauxites were previously known to occur on the Arabian platform only in the northeastern Sinai (Makhtesh Ramon area, southern Israel). They were formed during one of the major Mesozoic regressions, which included a large part of the Arabian plate at the end of the Triassic and beginning of the Jurassic. This event brought about the cessation of carbonate and sulfate deposition, which prevailed during most of the Triassic, and established a continental regime with a humid tropical climate, deep weathering of the bedrock, and deposition of terrigenous products of this weathering and erosion. Boemitic bauxite occurs in the Hettangian–Sinemurian Mishhor Formation (with Rhaetian–Norian beds locally preserved at the base) at the base of the terrigenous deposits (Fig. 1a).

In 1990 we discovered boehmitic allite and bauxite in the Mesozoic section at the foot of the Zubaydah Range of the Palmyra Mountains in southwestern Syria. The section is dominated by carbonate rocks, locally with minor sulfate sequences [4]. At the base of the Cretaceous section, below Albian beds, we observed a paleontologically barren terrigenous redbed sequence, as much as 60 m thick, that in places contained carbonate interbeds. Lenses of bauxite were found locally at the base of this sequence. These redbeds were dated as Early Cretaceous by comparison with the section in other regions of Syria. As a result of our studies and new fossil data, K. I. Kuznetsova has established that the Zubaydah Range of the southwestern Palmyrides includes Jurassic redbeds as well as Lower Cretaceous rocks. This series contains beds of three suites: the Neocomianearly Albian Abu-Dali, the Early Bathonian Mishg, and the pre-Bathonian (early Middle Jurassic) Zubaydah. Allite and bauxite were discovered in the latter.

The Zubaydah bauxite-bearing suite contains no fossils. Its upper age boundary is the Bajocian, since it is overlain by the Mishq suite with early Bathonian benthic foraminifera (identified by K. I. Kuznetsova): *Ammobaculites agglutinans* Orb., *Nautiloculina oolithica* Mohler, *Pseudomarssonella plicata* Redm., *P. reflexa* Redm., *Redmondensis medius* (Redm.), *R. primitivus* (Redm.), *R. lugeonia* (Septfont.), *Kilianina blancheti* Pfend., *Hauranina deserta* Henson, *Amijiella amiji* (Henson), and *Paulina paula* (Pazdro). Unfortunately, the dolomite and dolomitic limestone sequence underlying the suite is devoid of fossils, so the lower age boundary cannot be accurately delimited. Inasmuch as the structure and composition of the bauxite-bearing beds of the Syrian Zubaydah suite and the Mishhor Formation of Israel are quite similar, it is assumed that both formations are related to the major regression referred to above, which took place at the close of the

*Bauxite is used here for rocks that contain at least 28% Al_2O_3 and an $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio greater than 2.6. (Industrial Requirements for Mineral Resource Quality: Aluminum [in Russian], Gosgeoltekhizdat, Vyp. 35, Moscow (1962).)

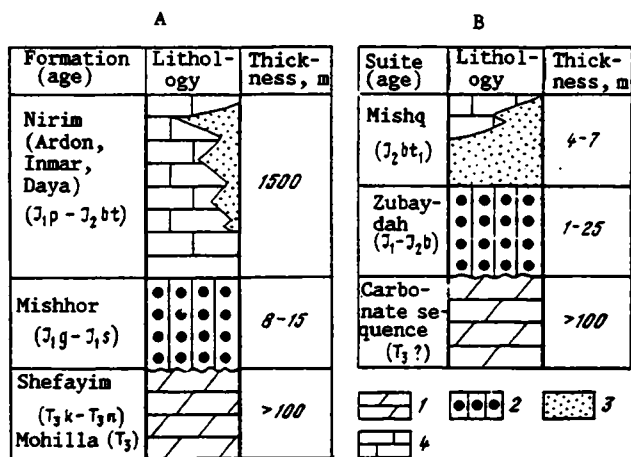


Fig. 1. Position of allite-bauxite beds in composite columnar sections of the Triassic and Jurassic (A, Makhtesh Ramon section, Israel; B, Zubaydah and Palmyride sections, Syria). 1) Dolomite and dolomitic limestone with local beds of limestone; 2) karst bauxite deposits (kaolinic clay, allite, and bauxite with inclusions of iron ore); 3) conglomerate, sandstone, siltstone, mudstone, or shale, locally with marl deposits; 4) limestone with local beds of dolomitic limestone and dolomite.

Triassic and beginning of the Jurassic. In Syria, as in Israel, the maximum regression probably occurred in Hettangian—Sinemurian time after beginning in the Norian—Rhaetian. The age of the Zubaydah bauxite suite thus ranges from earliest Jurassic to earliest Middle Jurassic (up to Bathonian), with a possible initiation in the Rhaetian—Norian of the Triassic. The age of the carbonate sequence underlying the Zubaydah suite is thus provisionally considered to be late Triassic.

COMPOSITION AND FACIES OF THE ZUBAYDAH BAUXITE-BEARING SUITE

The Zubaydah suite has been traced along the base of a single range in the southwestern Palmyrides for a distance of 800 m. The beds dip steeply (40°) to the north beneath younger Cretaceous beds. The suite unconformably overlies dolomites and dolomitic limestones of probable late Triassic age and is overlain along a sharp contact (but without apparent erosion) by marine clayey, marly, limy deposits (with lenses of oolitic iron ore) of the early Bathonian Mishq suite (see Fig. 1B). The suite is composed of continental red clays, allite, and bauxite with lenses of iron ore. It fills in an irregular karst surface and ranges in thickness from 3 to 25 m. Columnar sections showing the composition and distribution of rock types in the suite are presented in Fig. 2. We examine the principle rock types below.

Bauxite and allite, ranging in thickness from 1 to 12 m, were found in most of the sections studied (see Fig. 2, 3a-e). The bauxite locally contains lenses of clastic iron ore, or ferrallite. These aluminous rocks are subdivided into two structural types: 1) fragmental (Fig. 3a-c, f) and 2) pelitomorphic (Fig. 3d, e).

Fragmental rocks are further subdivided into conglomeratic-pebbly (fragmental-pisolitic) with clast and pisolite sizes of 1-2 cm or more, pebbly (fine pisolitic) with sizes less than 0.5 cm, and sparsely pebbly (sparsely pisolitic) where the clasts and pisolites make up less than 30% of the rock. Clasts are angular, sub-angular, or sharp, or have a stretched, oval shape, while pisolites are round.

The amount of fragmental material (clasts and pisolites) in the rocks is usually about the same. Large, uniform pisolites often appear to be rounded clasts or concretions. Many clasts have thin (tenths of mm) borders of boehmite, or locally are coated with hematite, so that they look like oolites or pisolites (see Fig. 3c).

Mineralogically the fragments and pisolites are almost identical. The pisolites are generally hematite-kaolinite-boehmite (pure boehmite is quite rare), and there are iron-rich varieties: goethite-hematite. The clasts commonly have more iron than the pisolites. They are also predominantly hematite-kaolinite-boehmite, with some hematite-kaolinite varieties, locally with relict basaltic textures. A few pebbles of limestone are found near the base of the bauxites.

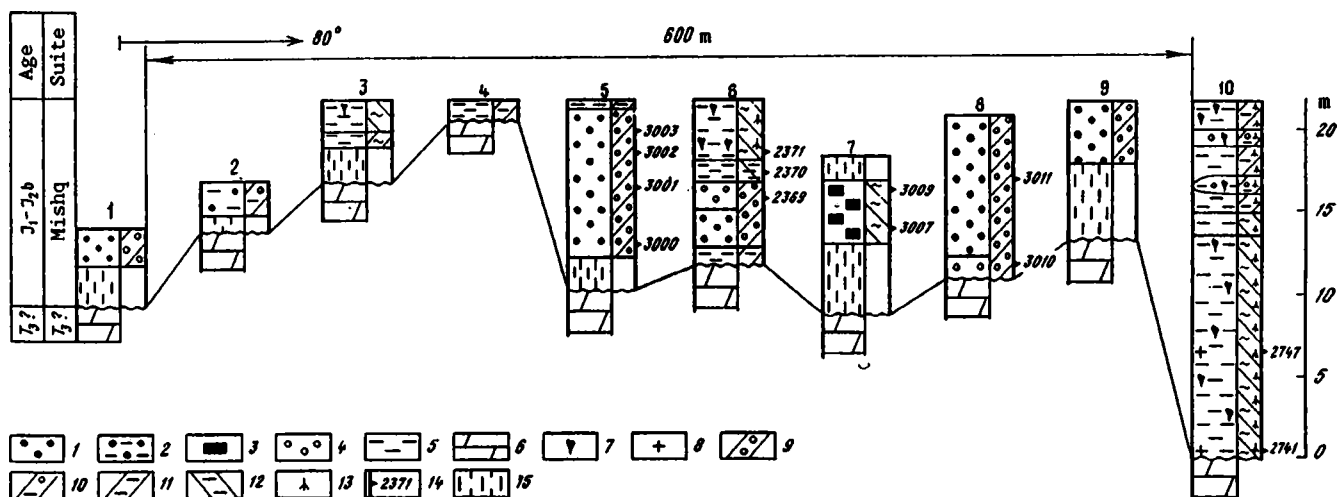


Fig. 2. Columnar sections of the Zubaydah bauxite-bearing suite in the Palmyra Mountains. Lithologies (left columns): 1-3) bauxite and allite (1, conglomeratic-pisolitic; 2, sparsely pisolitic; 3, pelitomorph), 4) conglomeratic-pisolitic iron ore, 5) clay, 6) dolomite and dolomitic limestone with limestone interbeds, 7) subvertical traces of paleosoil oxidation, 8) alunite. Deluvial and proluvial karst facies (right columns): 9) pebbly (pisolitic) sediment, 10) sparsely pebbly (pisolitic) clayey sediment, 11) clayey sediment, 12) clayey or pelitomorph allite-bauxite facies of karst and boggy lakes, 13) facies with paleosoils. 14) Sample locations; 15) section missing as a result of caving or surface disturbance. 1-10) Section numbers.

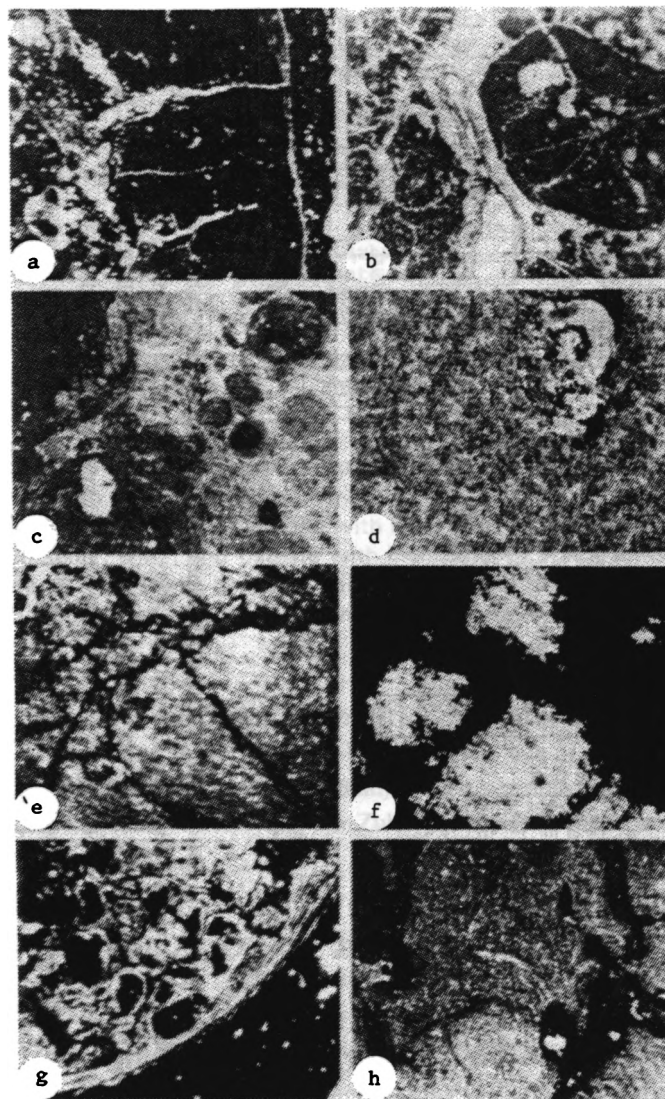


Fig. 3. Photomicrograph of thin sections of bauxite-bearing rocks, Zubaydah suite. a) Sample 2389 (section 3), fragment of a red boehmite-hematite pisolite with a lumpy interior (left) and kaolinite (white) in bauxite; b) sample 3004 (section 5), fragment of the center of a complex kaolinite-boehmite pisolite in bauxite; c) sample 3001 (section 5), small hematitic pisolites and a fragment of a larger one (upper left), with clots of boehmite (gray) in the cement, and a boehmite border (gray) around one of the hematitic pisolites in bauxite; d) sample 3007 (section 7), vermicular kaolinite in pelitomorphic white bauxite; e) sample 2371 (section 6) punctate-reticulate hematite and goethite in allite; f) sample 3002 (section 5), neogenic kaolinite (highly crystalline, bleached, granular) in bauxite; g) sample 2646 (section 6), fragments of highly weathered kaolinitized and oxidized tuff among pisolites in iron ore; h) sample 2756 (section 10), veinlets and spots of hematite and goethite in clay (a-g, with analyzer, $\times 70$; h, with polarizer, $\times 100$). See Fig. 2 for section numbers.

The cement in the bauxite is composed of very fine boehmite and kaolinite, generally with iron and commonly containing some leucoxene (anatase).

Formation of the allite and bauxite in a subaerial deluvial–proluvial environment as a product of the erosion of laterites is suggested by the poor sorting and orientation of the material (clasts and pisolites), the lack of laminations and the predominance of red and variegated colors. The attitude of the beds in the sections was clearly indicated, however, by variations in color, density of clast content, and size of clasts.

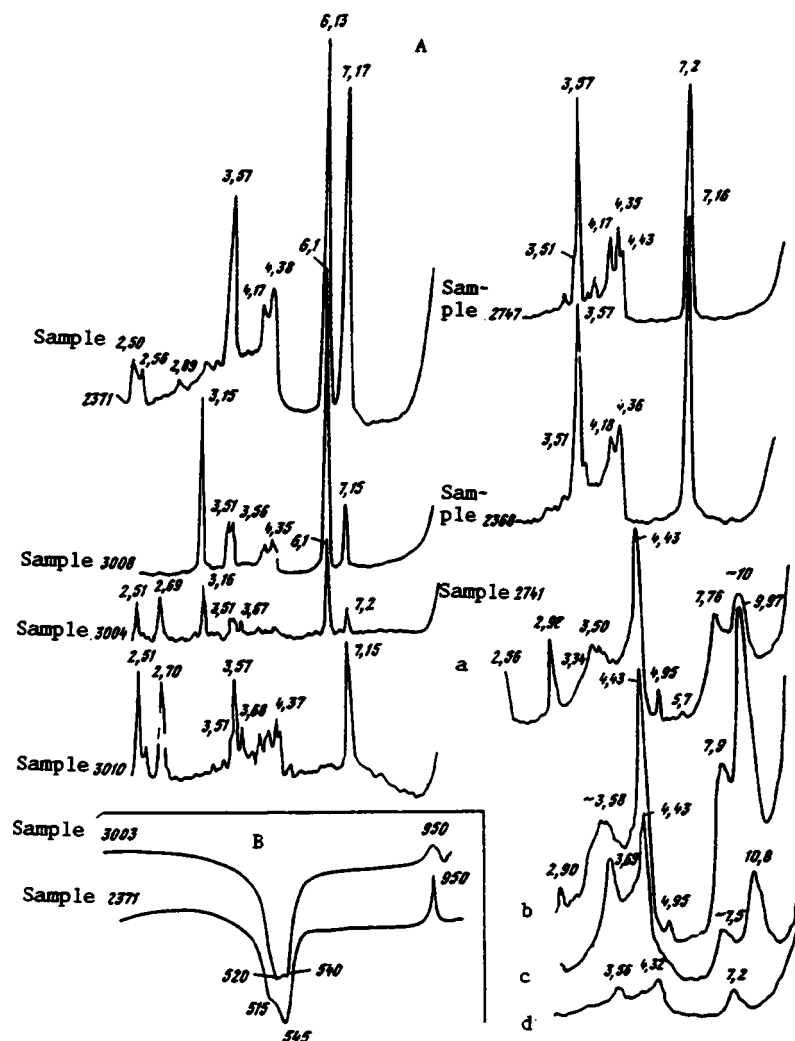


Fig. 4. Diffractograms and thermograms of samples from the Zubaydah suite (Fig. 2, sections 5-8, 10). A, Diffractograms: powdered (samples 3008, 3004, 3010, 2368, 2741a); oriented (samples 2371, 2747, 2741b); saturated in glycerin (sample 2741c); heated (sample 2741d). B, DTA thermograms. Sample 2371, boehmite-kaolinite allite; samples 3008, 3004, and 3003, kaolinite-boehmite bauxite; sample 3010, kaolinite-hematite iron ore; samples 2747 and 2368, kaolinitic clay; sample 2741, halloysitic clay (metahalloysite and hydrated halloysite) with minor alunite.

Pelitomorphic bauxite and allite are identified macroscopically by their uniform violet, white, yellowish-gray, and less commonly variegated colors and uniformly pelitomorphic texture. Microscopically, numerous tiny clots of neogenic boehmite can be seen (Fig. 3d). Sometimes clear fragments or pisolites of primary lateritic material, not visible macroscopically, are present.

The pelitomorphic aluminous rocks are basically composed of kaolinite-boehmite, with minor amounts of goethite and hematite (a few percent). These latter include both relicts (nodules and veinlets) and neogenic forms (vertical zones and veins, networks).

These deposits are generally well sorted, but the clast types are not evenly distributed: clear fragments are relatively sparse. The rocks have a distinct or indistinct horizontal lamination, but locally display no bedding at all. The bauxites and allites were formed at the bottom of karst depressions in a subaqueous lacustrine to swampy environment.

The composition of the Syrian pelitomorphic and clastic bauxites and allites is complex. Free aluminum occurs only in boehmite, as confirmed by x-ray and thermal analyses. Diffractometer patterns of typical samples show spacings of 6.13 Å, 3.15 Å, and others (Fig. 4, samples 2371, 3008, and 3004).

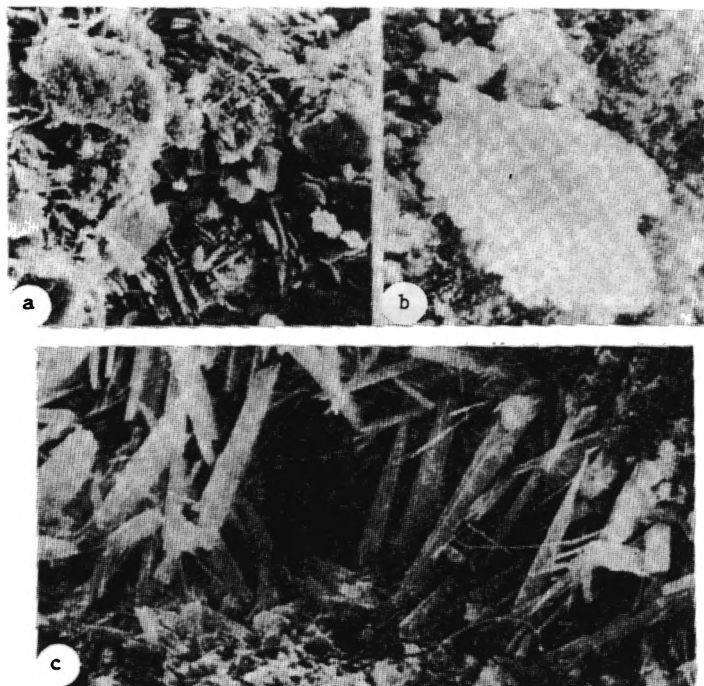


Fig. 5. Boehmite and halloysite in bauxite of the Zubaydah suite. Scanning electron microscope (scale: a, 10 μm ; b, 4 μm ; c, 20 μm). a) Sample 3008; b, sample 3002 (sections 5 and 7: isometric tabular crystals of boehmite in bauxite); c, sample 3002 (section 5): tubular crystals of halloysite filling open spaces in bauxite. See Fig. 2 for section numbers.

A profound endoeffect at 515-520° is seen on the thermograms (Fig. 4, samples 2371 and 3003) that is different from the kaolinite endoeffect.

In thin section under transmitted light boehmite appears as a translucent or yellowish fine-grained aggregate that occurs within the border area around pisolites, clots, patches, or colloform aggregates in the cement. Using the analyzer, the boehmite has a light gray interference color, and is locally almost opaque, i.e. optically isotropic. Under reduced lighting (oblique light) aphanitic aggregates of boehmite have a whitish, flaky coating like that on leucoxene.

With the use of the scanning electron microscope boehmite is seen to consist of very fine (1.5-3.5 μm) indistinctly crystalline aggregates with an isometric shape (Fig. 5a, b).

The clay mineral in the bauxite is mostly kaolinite of several generations. Primary kaolinite is finely dispersed in the rock, generally with more or less iron, and has a microscopic flaky texture. Secondary kaolinite fills fractures, pores, and voids in the rock, is bleached, and occurs in several forms: colloform, crystallized granular flakes (Fig. 3a, f), and vermicular crystals (Fig. 3d). The kaolinite was identified on diffractograms of allite and bauxite from the basal reflections, among others, of 7.15-7.17 Å (Fig. 4A, samples 2371, 3008, 3004), and on the thermograms by reactions at 540-545° and 950°C (Fig. 4B, samples 3003, 2371). A small amount of halloysite was found in the bauxite under the electron microscope, where its characteristic tubular crystals were seen filling voids and pore spaces (Fig. 5c). An earthy form of titanium, leucoxene, is commonly seen in thin section. The basal reflection of anatase, 3.51-3.52 Å, is generally present on x-rays. The presence of the iron-bearing minerals goethite and hematite is confirmed by the powder method, with hematite generally much more abundant.

Chemical analysis of the aluminous rocks in samples 3000, 3001, 3003, 3007, and 3011 of the Zubaydah suite shows that they correspond to high-silica bauxite and allite (Table 1). Their coefficient of silica ranges from 1.6-5.4, the Al_2O_3 content is 38-63%, Fe_2O_3 is 2-26%, FeO is 0.1-0.22%, SiO_2 is 11-28%, and TiO_2 is 2-4.5%. The bauxite is clearly not of high quality, and includes ferruginous varieties. White pelitomorphous bauxite (sample 3007) has the highest coefficient of silica (5.4).

Clay and iron ore are found along with allite and bauxite in the Zubaydah suite. They are briefly described below.

TABLE 1. Chemical Composition of Rocks in the Zubaydah Suite, wt. %

Component	Sample number											
	2371	3007	3009	3000	3001	3003	2370	2747	2369	3010	3011	3229
SiO ₂	28,39	11,68	27,44	15,33	16,18	16,84	36,85	42,88	25,67	31,79	24,28	20,30
TiO ₂	3,84	4,51	2,54	2,37	2,82	3,54	2,05	1,76	1,90	2,08	2,22	2,42
Al ₂ O ₃	49,41	63,47	52,42	43,46	44,24	51,36	33,81	38,53	24,73	31,76	38,03	20,14
Fe ₂ O ₃	2,46	2,08	3,01	26,27	23,19	13,31	13,10	2,03	36,26	21,66	22,88	45,16
FeO	0,10	0,22	0,27	0,15	None	0,15	0,19	0,14	0,39	0,14	0,22	0,15
MnO	Trace	0,01	0,01	0,04	0,02	0,01	None	None	None	0,02	0,01	0,10
CaO	1,92	0,69	0,47	0,81	0,68	0,79	1,20	0,5	1,45	0,72	0,81	1,22
MgO	None	0,21	0,08	0,25	0,61	0,24	None	None	0,52	0,21	None	0,34
Na ₂ O	0,11	0,17	0,08	0,06	0,06	0,06	0,56	0,06	0,11	0,77	0,16	0,40
K ₂ O	0,02	0,11	0,06	0,14	0,02	0,11	0,22	0,07	0,11	0,14	0,13	0,22
H ₂ O ⁻	0,76	1,57	0,71	0,65	0,80	0,65	0,78	0,71	0,72	1,79	0,61	1,14
H ₂ O ⁺	12,88	13,81	12,72	9,55	11,04	8,97	11,73	9,90	8,59	10,05	10,81	8,01
CO ₂	None	None	None	None	None	None	None	None	None	None	0,35	None
C	"	"	"	"	"	"	"	"	"	"	0,07	"
P ₂ O ₅	"	0,031	0,06	0,03	"	0,02	"	0,06	"	"	None	"
SO ₃	"	1,95	None	None	"	None	"	1,04	"	"	"	"
Ign. loss	—	—	—	—	—	—	—	2,35	—	—	—	—
Total	100,41	99,13	99,17	99,11	99,48	99,38	100,49	100,58	100,54	100,54	100,48	100,17
Al ₂ O ₃ /SiO ₂	1,7	5,4	1,9	2,8	2,7	3,0	0,92	0,90	0,96	1,0	1,6	1,0

Note. Sample 3007, pelitomorphic yellowish-gray to white bauxite; samples 3000, 3001, 3003, pisolitic to clastic red bauxite; samples 2370, 2371, 2747, 3009, boehmite-kaolinite clay and allite; samples 2369, 3010, 3011, reddish-brown pisolitic ferrallite; sample 3229, reddish-brown to variegated massive iron ore. Analysis performed in the chemical laboratories of the Geological Institute and Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences.

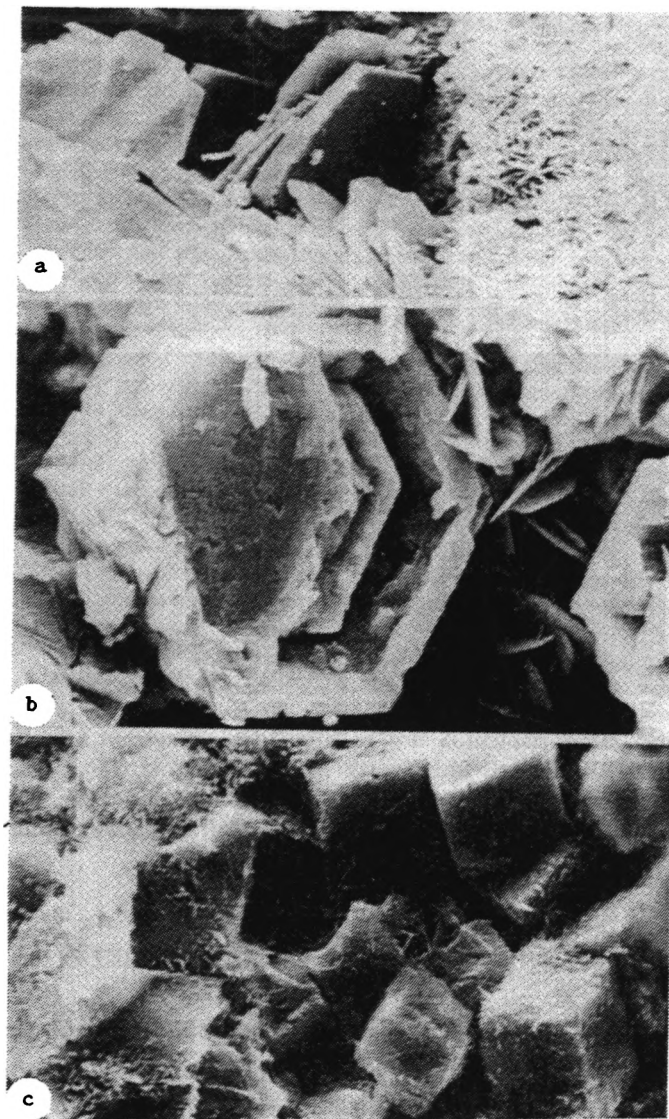


Fig. 6. Scanning electron microscope views of kaolinite, hematite, and alunite crystals in clays of the Zubaydah suite (Fig. 2, section 10). Scale, μm : a, 20; b,c, 4. a) Sample 2753, large and small hexagonal crystals of kaolinite; b) sample 2753, highly corroded large hexagonal crystals of kaolinite and fine, well formed crystals; c) sample 2741, aggregates of cubic crystals of alunite and kaolinite in micropores in halloysite clay.

Beds and lenses of clay are abundant in the suite (Fig. 2). Deluvial—proluvial deposits are generally red in color, bedding is generally lacking, and fine (sandy) grains (less commonly pebbly or pisolitic clasts) of eroded laterite are typically present. Proluvial—lacustrine deposits are horizontally bedded. Lacustrine to swampy deposits are white, yellow, or purple, well sorted, and have horizontal bedding or none at all. Clays of this suite have commonly been altered to ferralitic soils with whitish or ferruginous vertical patches and veinlets (commonly tubular) developed along ancient root traces. The texture of these ancient soils is well evident in thin section and is emphasized by the unusual reticulate and punctate appearance of the iron hydroxides (Fig. 3h).

All of the clays are composed of kaolinite group minerals, mainly fine flakes of optically randomly oriented primary kaolinite. Also commonly seen in thin sections of clay, as in bauxites, is colloform and coarse flaky recrystallized kaolinite in voids, joints, and pore spaces. Diffractograms of the clay confirm the kaolinitic composition (Fig. 4A, samples 2747, 2368), with minor amounts of only anatase and iron hydroxides. Sample 2370 typifies the chemical composition of the clay (Table 1).

Electron microscope study of the clay reveals a number of different types of kaolinite. There are both large and small hexagonal crystals (Fig. 6a, b), including highly corroded examples of the large ones (Fig. 6b). Solitary or aggregated tubular crystals of halloysite in the clay can only be seen by means of the electron microscope; it is a very minor constituent and is not picked up on x-ray patterns. The only exception is sample 2741 in section 10 (Fig. 4A), where halloysite is the principal rock-forming mineral. It has moreover been subdivided into hydrated halloysite, with a basal reflection of 10 Å, and metahalloysite (7.8 Å reflection). This halloysite clay forms secondary lenses and patches within the primary kaolinite at the base of section 10, and contains finely divided alunite. The latter is responsible for the basal reflections at 4.95 and 2.9 in the powder patterns of 2741 (reflections at 2.23 Å, 1.897 Å, 1.747 Å, and others that appear at the lower corner outside of the figure). Alunite forms aggregates of cubic crystals under the electron microscope (Fig. 6c).

A small amount of alunite and secondary, recrystallized kaolinite were found within the primary clay in sample 2747 from section 10. This is reflected in the presence of 1.04% SO_3 in the sample (Table 1).

Lenses of conglomeratic (clastic-pisolitic) iron ores of deluvial—proluvial origin were found in bauxite or clay in some sections of the suite (Fig. 2, sections 6, 8, and 10).

According to the chemical analyses (Table 1, samples 2369 and 3010) the Fe_2O_3 content in these rocks ranges from 21-66% to 32.26% and FeO from 0.14% to 0.39%. The silica coefficient does not exceed 1.0. Iron minerals (hematite and minor goethite), in addition to kaolinite, occur in the clasts and cement. Lateritic clasts (pebbles and pisolites) are distinguished by color (red, variegated, and whitish) and composition (ferriferous-clayey); they include relict highly weathered basaltic tuff (Fig. 3g) completely replaced by kaolinite and iron hydroxides. Basal reflections of hematite (3.68, 2.70, 2.51, 2.20, 1.691 Å, and others), and a minor amount of anatase (3.51 Å) and locally goethite, in addition to kaolinite, were determined from powder diffraction patterns of the iron ore (Fig. 4A, sample 3010).

Primary and secondary fine and coarse folia of well crystallized kaolinite were found in the iron ore just as in the bauxite.

It is noteworthy that, just as in the stratigraphically higher early Bathonian Mishq formation, quartzose terrigenous rocks have not been encountered in the bauxite-bearing continental Zubaydah suite of the Palmyrides. The Jurassic redbeds thus differ from the overlying lower Cretaceous terrigenous redbeds, where quartzose sandstones and siltstones are common.

ORIGIN AND SECONDARY ALTERATION OF ZUBAYDAH ALUMINOUS ROCKS

Environment of Deposition. The data cited above on the makeup and composition of the bauxite-bearing rocks of the Palmyrides suggests that the source of the sediments was red lateritic weathering mantle on quartz-free rocks, which were eroded at the end of the Triassic or beginning of the Jurassic and deposited in karst sinks and depressions. Sediments were deposited in deluvial or proluvial facies, or locally in swampy lakes. These facies, as well as the poor rounding of pebbly laterite clasts (pisolites) suggest transport of terrigenous material only a short distance from the source. Perhaps small local uplifts of the emergent carbonate platform took place in the Palmyrides after regression of the Triassic sea, whereupon not only the exposed Triassic sulfate-carbonate rocks were eroded, but also the weathered mantle of quartz-poor silicate rocks: basaltic lavas and tuffs. Kaolinitized clasts of the latter have been established in Zubaydah suite rocks (Fig. 3g). Bedrock exposures of such Triassic-Jurassic volcanic rocks with a weathering mantle have not yet been found in the Palmyrides (only in the lower Cretaceous). Considering the poor exposures and thus the lack of study of rocks of this age, it is possible that such volcanic sources will be discovered, however.

Significantly, in other platformal regions of Syria (Antilebanon, core holes at the town of Abba in the north) sequences of basalt, diabase, and spilites occur in latest Triassic to earliest Jurassic rocks [4], supporting the presence of volcanism in the study area.

Secondary Alteration. After deposition of bauxitic redbeds in the karst basin, they were subjected to transformation during diagenesis, epigenesis, and by hydrothermal activity.

During the stage of diagenesis, swampy lake facies rocks, which contained organic matter, became lighter in color; this was associated with the loss of iron hydroxides from the clay and fine laterite clasts. The clays, bauxite, and allite thus became whitish or slightly ferruginous (light purple or yellow) and contained a total of less than 2.5-6% oxides of bivalent or trivalent iron.

Under subaerial conditions, where deluvial—proluvial redbeds or swampy karst lake sediments accumulated, the effects of ancient ferrallitic soils were commonly felt. Remnants of these effects are often found in aluminous or clayey rocks of the Zubaydah suite (Fig. 2). With the amalgamation of individual thin (0.2-3.0 m) beds of different ages, altered soil sequences up to several tens of meters thick were formed (see section 10). Sections of ancient soils, and their chief textural features, have much in common with modern ferrallites [5, 6] or their early Paleogene analogues in Kazakhstan [16, 17]. They show up nicely in the section due to light-colored and ferruginous spots with veinlets and nodules of hematite and goethite, oriented vertical to bedding along roots or joints in the ancient soils. The degree of alteration increases from the base of the section upward, and they have lost most of the original bedding and have become lumpy, porous, and full of cracks. These cracks and voids are commonly filled with iron hydroxides or clay, generally optically oriented (colloform). Iron oxide compounds commonly form an unusual reticulate or punctate appearance in thin section, similar to colonies of ferriferous bacteria we have seen previously in lower Paleogene soils of Kazakhstan [14]. These ferrallitic soils have been subdivided into lateritic and ferriferous-kaolinitic [17]. The substrate of the ancient lateritic soils of Kazakhstan has been desilicified and additional bauxites have been formed from kaolinitic clays or allite (or the quality of the original bauxites has been improved); the ferriferous-kaolinitic soils were formed on red kaolinitic clays, the alteration of which was actually associated only with textural changes and redistribution of the iron hydroxides and kaolinite.

Ancient ferrallitic soils in the bauxitic section of the Zubaydah suite have not been studied in detail. The available information suggests that most of them are of the ferriferouskaolinitic variety. Therefore their formation on a kaolinitic substrate did not lead to secondary lateritization and the origin of minerals of free aluminum.

Tubular clay-iron cuirasses with a high iron content have been formed in a number of cases in the cover of eluvial deposits. One such cuirass is well exposed and clearly evident between sections 9 and 10 (Fig. 2). It is composed of hematite with minor goethite and kaolinite, and qualifies as an iron ore (Table 1, sample 3229, Fe_2O_3 45.16%, FeO 0.15%).

The question of whether there were buried lateritic soils in the Zubaydah suite that were involved in secondary bauxite formation remains unresolved. It was noted above that in the allites or bauxites studied a reticulate soil texture was evident (Fig. 3e). It is still unclear, however, whether the free aluminum in such soils originated as the result of desilicification of kaolinitic clay or by some other means (preserved from the soil-forming substrate, or arose as a result of the breakdown of clay minerals in ancient karst basins by rainwater or groundwater).

Significantly, in nearby Israel buried soils are widespread in the early Jurassic Mishhor Formation, and they had a major part in forming the texture of the rock [21-23]. Unfortunately, the problem of chemical and mineralogical alteration of the aluminosilicate substrate was not examined in these studies. Comparing their outward appearance, makeup, and salient features, the ancient Syrian soils and the Mishhor types can be considered outwardly identical.

These studies suggest that secondary lateritization of rocks in ancient karst depressions of the Zubaydah suite was caused by rainwater and groundwater washing through kaolinite-bearing sediments and bringing about their desilicification. This process is associated with the appearance of finely dispersed or microclotted boehmite borders around ferriferous pisolites and the formation of most of the boehmite in pelitomorph bauxite.

Thus the loss of iron compounds from the rock as a result of diagenetic bleaching in a swampy lake facies, and the desilicification of kaolinite-bearing substrates by washing with rainwater or groundwater, and possibly by their alteration in ancient lateritic soils, can be included in the postsedimentational processes that led to enhancement of the quality of the bauxites studied, or to promoting secondary bauxitization.

In addition to processes improving the quality of bauxite and allite, retrograde alteration that produced secondary resilicification and kaolinitization was observed. In thin section, secondary kaolinite generally fills cracks, pores, and voids in the rock. As a rule, it is optically oriented, unlike most of the original fine flaky kaolinite. The varieties of this material are described below.

Colloform kaolinite is widespread in aluminous and clayey rocks of the Zubaydah suite. In transmitted light it is generally light yellow, with interference colors (from gray to yellow) under crossed nicols. It has been noted in a number of papers [15-17] that clay with colloform texture frequently originates under the effects of modern or ancient groundwater on sediments. In such cases it may form from natural, optically nonoriented clay by a transition to a colloidal state and subsequent precipitation, or chemically by interaction with organic and mineral matter in soil solutions and material leached from the bedrock. It is likely that colloform clay in the suite formed under the influence of ancient soils or groundwater, for which the evidence is quite clear in these deposits.

Coarse platy, crystallized, granular kaolinite is commonly found in all of the lithological varieties of the suite, localized in cracks, voids, and pore spaces. It is very white in thin section in transmitted light and light gray under crossed nicols. This type of kaolinite has been restricted to the products of hydrothermal activity or to epigenesis by [9]. Crystallized kaolinites in hydrothermal rocks are quite likely in the Jurassic–Cretaceous redbeds of Syria. During this time Syria was located in the active part of the African-Arabian platform, where, as noted above, volcanic activity and faulting took place and can be traced in the Palmyride zone. Our studies in Syria, which have not yet been published, confirm the effects of Jurassic–Cretaceous hydrothermal activity on sedimentation both in the seas and on land. Low-temperature hydrothermal activity in the Palmyrides, where early Middle Jurassic and Early Cretaceous continental terrigenous redbeds accumulated as products of the erosion of laterites or kaolinitic weathering mantles, led to intensive secondary alunitization and gypsification of the bedrock and the appearance of crystallized kaolinite and, at times, weak silicification.

It should be noted that the paragenesis described above, which includes alunite, gypsum, chalcedony, and kaolinite, is typical of modern-day low-temperature hydrothermal activity [7, 8, 12, 13, 18, 20]. These occurrences have so far been studied and described only in tectonically active foldbelts, however, where the hydrothermal activity has usually taken place in volcanic rocks and caused their alteration. In the active part of the Syrian platform the hydrothermal activity affected typical continental sediments, products of the erosion of the weathering mantle. These conditions had not been encountered in the earlier studies.

Alunite is the best indicator of hydrothermal activity. This mineral is also known to form in sediments, however. Alunite is rarely and only locally encountered in bauxite-bearing sequences, where it forms grains and nodules 1 mm to 10 cm, sometimes 1 m, in size [1]. Bardossy [1] believes that the formation of alunite is associated with the oxidation of pyrite; the formation of sulfuric acid, and the ensuing reaction with aluminum minerals. On the Arabian peninsula, examples of such nonhydrothermal alunites are found in the middle Jurassic carbonaceous sandy–clayey Inmar formation of Israel [20]. Potassium and potassium–sodium alunites form patches, lenses, veins and cement in quartzose sandstones in Jurassic–Cretaceous redbeds in the Palmyra Mountains of Zubaydah, Rimah, and Mazar; the sandstones reach 40 m in thickness in the Lower Cretaceous of Mazar. Widespread alunitization in unfaulted zones and the association of alunite with gypsum, secondary kaolinite, and locally with chalcedony are not present in the carbonaceous, pyritiferous rocks underlying and overlying Jurassic and Cretaceous redbeds of the Palmyrides. This suggests that the mineral association is not due to sulfuric acid weathering of the sediments and that it is likely the result of low-temperature hydrothermal activity.

It should be noted that the secondary kaolinitization of lower Jurassic bauxite-bearing rocks in the Zubaydah area of the Palmyrides is often not accompanied by alunitization, or by gypsification or silicification either. The alunite occurs as patches and thin lenses (up to 10–15 cm) at the base of section 10 (Fig. 2) along with metahalloysite and hydrated halloysite (Fig. 3A). There is a small amount of clay in sample 2747, higher in the section, which according to the chemical analysis (Table 1) is associated with SiO_2 . It is suggested, moreover, that hydrothermal alteration of various lower Middle Jurassic rocks in the suite (clayey, aluminous, ferriferous), unlike the Lower Cretaceous, has led to the formation of the crystallized kaolinite (rarely halloysite) described above and is locally accompanied by gypsification and alunitization. The proposal that this crystallized kaolinite is of hydrothermal origin needs verification in further studies, however.

The foregoing information supports the conclusion that Jurassic continental sediments in paleokarst basins have been profoundly altered. One group of secondary processes improved the quality of the primary aluminum ore or promoted local bauxitization, while another, on the contrary, led to kaolinitization and the breakdown of bauxite.

FEATURES OF TRIASSIC–EARLY JURASSIC BAUXITE FORMATION IN SYRIA AND ENVIRONS

Analysis of the data suggest that at the end of the Triassic and beginning of the Jurassic a stage of deep chemical weathering and bauxite formation took place on the Arabian platform. In addition to the Zubaydah bauxite-bearing suite in Syria and the Mishhor Formation in Israel, the formation of lateritic soils in the late Liassic (Toarcian) Marrat Formation and the Triassic–Liassic Minjur Formation has been noted [24]. A large number of factors favored the formation of bauxite on the Arabian platform at this time. A global marine regression led to the exposure of vast areas. Epirogenic uplift and a hot, humid climate brought about the formation of a lateritic weathering mantle. Early Mesozoic basaltic

magmatism provided a quartz-free aluminosilicate substrate favorable for the development of lateritic eluvium. The widespread development of a platform carbonate sequence and its weathering led to the formation of a karst surface of relief, in the depressions of which the products of erosion of the lateritic weathering mantle accumulated and secondary bauxitization took place in a humid paleoclimate. In this connection the idea that essentially the entire Arabian platform was dominated by an arid or semiarid climate [3] during the Jurassic seems to us unjustified. This view is contradicted by the presence of lithologic indicators of humid conditions during the Early to earliest Middle Jurassic. These include not only the laterite weathering mantles and bauxite deposits studied, but also carbonaceous and iron ore formations around the entire northwestern margin of the Arabian platform (from the Sinai to Iraq) [20, 25].

A stage of bauxite formation during the latest Triassic to the earliest Middle Jurassic has been traced over a wide region of the Arabian platform along the southern margin of the Mesotethys sea. According to Bardossy [1], Late Triassic karst bauxites are found in the Central Iranian Plateau, while in the Taurus Mountains of southern Turkey Jurassic lateritic bauxites are enriched in iron. Mediterranean karst and lateritic bauxites of this stage are present in Greece, Yugoslavia, Sicily, Albania, and along the western Mesotethys in the south of France, in Switzerland, and in Spain [1, 19, 24]. In the northern part of the Mesotethys Triassic–Jurassic karst bauxites have been found in Uzbekistan, Tadzhikistan, Kirgizia, Kazakhstan [2], and Afghanistan [11]. It should be noted that the quality of bauxites in geosynclinal belts, where coastal karst bauxite (in carbonate sections) predominates is quite high, while in platformal areas such as the former USSR and elsewhere (including the Arabian plate) it is generally low as a result of widespread secondary processes of resilicification [1, 2].

In tracing this stage laterally, there is a tendency to shorten its duration from the end of the Triassic to the Lower or earliest Middle Jurassic in the east and central part of its range (Asia Minor and Central Asia, the Arabian peninsula, the Balkans, Yugoslavia, Sicily) to the Middle Jurassic on the west (the south of France, Switzerland, Spain). The bauxite can be subdivided into boehmitic, boehmitic-diasporic, and diasporic; a gibbsite-boehmite variety is rarely encountered (only in Spain).

We note in general that bauxite of the Syrian Palmyrides is firmly placed in the bauxite-forming epoch at the end of the Triassic and beginning of the Jurassic, which has been preserved in coastal areas in many regions along the southern, northern, and western margin of the Mesotethys. After regression of the sea, a broad continental landscape was exposed on the northwestern part of the Arabian platform, in parts of Syria and Israel (as well as nearby regions of the Sinai, Lebanon, Jordan, and Iraq), which had similar conditions favorable for bauxite formation (climatic, tectonic, paleogeographic). New discoveries of allites and bauxites of this age are thus possible in these areas.

LITERATURE CITED

1. G. Bardossy, *Karst Bauxite*, New York (1982).
2. B. A. Bogatyrev, *Triassic–Jurassic Weathering Mantle and Bauxite in the Southern Part of Central Asia* [in Russian], Nauka, Moscow (1980).
3. V. A. Vakhromeev, *Paleofloristics, Phytogeography, and the Climate of the Mesozoic and Cenozoic* [in Russian], Nauka, Moscow (1990).
4. *Geology and Mineral Deposits of Foreign Countries. Syria* [in Russian], Nedra, Leningrad (1969).
5. M. A. Glazovskaya, *Soils of the World* [in Russian], Moscow Univ. (1972).
6. F. Dushofur, *Basic Soil Science* [in Russian], Progress, Moscow (1970).
7. V. A. Eroshchev-Shak, *Hydrothermal Subsurface Lithogenesis in Areas of Active Volcanism, Kurile-Kamchatka Region* [in Russian], Doct. Sci. Dissert., Geol. -Miner., Geol. Inst. Akad. Nauk SSSR, Moscow (1987).
8. V. A. Eroshchev-Shak, A. S. Bukin, and V. I. Cherkashin, "Kaolinites of modern hydrothermal deposits and hydrothermal lakes and their structural features," *Litol. Polezn. Iskop.*, No. 3, 89-106 (1991).
9. V. T. Luk'yanova, G. A. Sidorenko, M. Yu. Ivanova, et al., *Typomorphic Features of Kaolinites of Various Origins and the Determination of Genetic Types of Deposits*, in: *Genesis and Resources of Kaolinitic and Refractory Clays* [in Russian], Nauka, Moscow (1990), pp. 155-164.
10. N. G. Minashina, "Optical orientation of clays in soils," *Pochvoved.*, No. 4, 15-22 (1958).
11. K. Ya. Mikhailov, V. M. Moralev, Yu. S. Perfil'ev, and M. A. Chal'yan, "Bauxite content of Mesozoic deposits in the southern part of the Afghano-Tadzhik depression," *Razv. Okhran. Nedr.*, No. 7, 60-62 (1969).

12. S. I. Naboko, *Volcanism, Hydrothermal Processes, and Ore Formation* [in Russian], Nedra, Moscow (1974).
13. S. I. Naboko, *Metal Content of Modern Hydrothermal Rocks in Areas of Tectonic and Magmatic Activity* [in Russian], Nauka, Moscow (1980).
14. A. P. Nikitina, Yu. G. Chekhovskii, T. V. Aristovskaya, and L. V. Zykina, "Role of microorganisms in the formation of lateritic weathering mantles and bauxites," *Kor. Vyvet.*, No. 20, 179-191 (1991).
15. E. I. Parfenova and E. A. Yarilova, *Mineralogical Investigations in Soil Science* [in Russian], Izd-vo Akad. Nauk SSSR, Moscow (1962).
16. Yu. G. Tsekhovskii, *Lithogenesis of Continental Variegated Silica-Goethite-Kaolinite Formations* [in Russian], Nauka, Moscow (1973).
17. Yu. G. Tsekhovskii, *Sedimentogenesis and Lithogenesis of Humid Redbeds at the Boundary of the Cretaceous and Paleogene in Kazakhstan* [in Russian], Nauka, Moscow (1987).
18. A. V. Shcherbakov, A. I. Voznesenskii, and V. I. Dvorov, *Hydrochemistry of Lithogenesis, Eastern Carpathians* [in Russian], Nauka, Moscow (1987).
19. M. Goldberg and G. M. Friedman, "Paleoenvironment and paleogeographic evolution of the Jurassic system in southern Israel," *Bull. Israel. Geol. Surv.*, No. 61, 1-44 (1974).
20. R. Goldbery, "Early diagenetic, nonhydrothermal Na-alunite in Jurassic flint clays, Makhtesh Ramon, Israel," *Bull. Geol. Soc. Am.*, **89**, No. 5, 687-698 (1978).
21. R. Goldbery, "Sedimentology of the Lower Jurassic flint clay bearing Mishhor Formation, Makhtesh Ramon, Israel," *Sedimentology*, **26**, No. 2, 229-251 (1979).
22. R. Goldbery, "Paleosols of the Lower Jurassic Mishhor and Ardon Formations (Makhtesh Ramon, Israel)," *Sedimentology*, **29**, No. 5, 669-690 (1982).
23. R. Goldbery, "Structural analysis of soil microrelief in paleosols of the Lower Jurassic (Makhtesh Ramon, Israel)," *Sed. Geol.*, **31**, No. 2, 119-140 (1982).
24. F. Hirsch, "The Arabian subplate during the Mesozoic," in: *The Geological Evolution of the Eastern Mediterranean*, Geol. Soc. Spec. Pub. No. 17, London (1984), pp. 217-223.
25. J. Petranek and S. Jassim, "Iron ore deposition within the Arabian Peninsula in time and space," *J. Geol. Soc. Iraq*, **13**, No. 1, 179-186 (1980).

EVAPORITES AND ORE GENESIS.

PART 1. MINERAL FORMATION IN POTASSIUM-BEARING FORMATIONS

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This paper reviews basic problems of evaporite formation. Lithological complexes of K-rich formations tend to consist of zones. The mineralogy and evaporite formation conditions are described during formation of associated ore and nonmetallic mineral deposits. Criteria in evaluating the entire complex are being presented.

TECTONIC CONDITIONS OF EVAPORITE FORMATION

For a long time, geologists considered evaporite development only a process that forms salt minerals, anhydrite (gypsum) and carbonate rocks. Other mineral components, such as B, Br, Pb, and Cs have later been discovered in evaporites. Because evaporite deposits include salt minerals, only salt beds and layers were originally investigated in detail. Anhydrite-carbonate beds of evaporite formations were superficially studied by macroscopic or formal means. Even after the recognition of native S-deposits and celestite-bearing horizons in evaporites, no attention was paid to mineral genesis processes in anhydrite-carbonate-terrigenous beds of evaporite formations. Well-known geologists and evaporite experts of previous generations believed that the medium of salt basins prevented even minor ore mineralizations and salt rocks are entirely devoid of metals. Only insignificant traces of copper was thought to occur in salt rocks.

More information became slowly available on the mineral genesis in evaporite formations in the past two-three decades. The first studies and publications in this country [8] and abroad [16, 17] noted the presence of various stratiform ore and nonore mineralizations. These rocks studies led to the understanding of basic characteristics and specific conditions in the distribution patterns of stratiform and vein ore mineralizations. Their development pattern was determined through studies both of evaporite and ore-forming processes. The mineral genesis was most varied and the intensity of stratiform ore mineralization greatest in K-rich formations in sections, represented by the most complete lithological assemblages. This is due to the fact that each assemblage corresponds to a given type of mineralization, the circumstances of which favored specific depositional, diagenetic and epigenetic conditions [8, 9].

The evaporite formations formed in specific salt basins, generally outlined by faults that, to a limited extent, also influenced subsalt units. They have undergone intensive subsidence during salt formation. Large evaporite basins periodically were filled by sea water, while small basins (salt lakes) generally were of continental origin or formed due to erosion and redeposition of ancient salts from salt-bearing bedrocks. The structural association of evaporite basins, related to large mobile crustal elements of the Earth is well explained by the geosynclinal and tectonic plate theories.

According to the geosynclinal theory, the largest evaporite basins are associated with platform margins. They surround them in regions of piedmont and exogonal basins. Within, platform-type evaporite basins are associated with grabens and aulacogens. Inside intermontane massifs, they form along marginal orogenic zones, interior piedmont depressions.

According to the tectonic plate theory, the most important periods of salt accumulation are also associates with rift development and orogenic phases. Piedmont basins formed during these times. Most K-rich formations developed under geodynamic conditions along passive platform (plate) margins, and also through rifting [2]. Tectonic mobilizations thus impacted Lower Cretaceous K-rich formations in Brazil and the Congo, while continental plates became fractured and the Atlantic Ocean opened up. The lithosphere was compressed during formation of younger, Neogene evaporites in Alpine and Himalayan regions (Spain, Sicily, Precarpathian region, Armenia and Iran). Under these conditions lithospheric plates experienced underthrust and collision during the final stages of ocean closing. The largest potassium-rich basins thus are

associated with compressed, convergent zones, or with divergent belt of tectonic extension in piedmont basins or rift zones [1].

Both the geosyncline and the plate theory explain the basic problems of evaporite genesis and development of large evaporite formations very well. Gray areas of understanding prevail only in the details or involve certain evaporite regions. Problems still remain in explaining interaction between evaporite formation and subduction.

Specifics in tectonic structures, associated with evaporite basins did determine not only the character of evaporite development [12] but also of the ore development, accompanied by evaporite genesis. This involves stratiform and superimposed realizations. Longitudinal faults flank evaporite basins in incompletely defined areas of thick, salt-rich lithocomplexes that included evaporite formations. Salt thickness was reduced along flank zones of the evaporite basins and above escarpment flanks. Salt-free anhydrite-carbonate-terrigenous lithocomplexes occur here. In zones of flank fault zones, ore and nonore mineralizations that accompany evaporite formations are primarily linked to such lithocomplexes. In similar rocks, the lower evaporite unit and the ore and nonore beds that directly underlie it occupy significant areas. This may be due to the fact that the associated mineral components were introduced to the evaporite basin and its deposits not only from adjacent continents and along flanking faults, but also through transverse faults. The faults formed fault blocks in the subsalt basement. Except for mineralized waters discharged from the continent, only under these conditions may subsalt brines penetrate evaporite basins and later the evaporite horizons. These brines carried associated mineralization of different origin and were shielded by the evaporite units.

Tectonics thus played a crucial role in the transport of associated ore and nonore mineralizations in regions with evaporite deposits; both in evaporite basins and formations. The presence of fractures that penetrated the subsalt basement was essential. Faults extended upward into evaporite formations. The lithology; presence of anhydrite-carbonate horizons in the role of hydrochemical barriers, played an important part in establishing mineralizations in evaporite formations and enclosing terrigenous-carbonate beds. This fact explains sharp differences in the ore content between various lithocomplexes and horizons of evaporite units, as well as their accumulation, mostly in salt-free lithocomplexes and the enclosing beds. It also accounts for the absence of ore components in rocks with the highest salt content.

The association of evaporite formations, in particular K-rich evaporates with highly mobile and intensively subsided large structures of the Earth's crust, suggests a greater likelihood of ore brine migration in these areas, both in deep units [4, 6], and their formation in hydrocarbon-bearing deposits that underlie salt beds [5]. Consequently, deep hydrotherms and ore components in rocks may be the source of ore matter in brines. Chlorite brines that are good solvents, may have percolated through these rocks. Thus, the tectonic conditions and physicochemical media in the evaporite regions favored not only evaporite formation, but also extraction, migration and settling of ore and some nonore matter [3, 7, 9, 13].

Ore genesis in the marginal zones of evaporite areas was also favored by the fact that barrier reef quite often surrounded evaporite formations, or the reefs directly underlie the evaporites. They usually formed along linear fractures that framed them and conducted ore solutions from even great depths. Barrier reefs are known from many evaporite areas of the former USSR and abroad [1, 14]. They often are associated with oil and gas deposits. In many evaporite areas their ore content often has not been studied in great detail. Large Pb-Zn deposits, such as Pine Point deposit in Canada are associated with reefs that frame the Devonian K-rich Prairie Formation on the northwest. Thus, ore genesis in evaporite area barrier reefs also displays a connection between favorable tectonic (fault zone association) and lithologic (sulfate and carbonate-bearing media) factors. Hydrogen-sulfide barriers formed near the border between carbonate rock and anhydrite. ore components were trapped along this boundary.

According to the plate theory, localization of evaporite formations in large tectonic structures that subsided fast along faults, provides favorable conditions for more intensive export of ore matter from deep sources. Naturally, vertical dislocations were more favorable for ore deposition than were overthrusts. The most favorable for ore formation are framing faults that occur in zones with marginal anhydrite-carbonate complexes of evaporite formations and barrier reefs. The intersection between marginal and transverse faults would be expected to produce nodal point ore deposits.

The Zn-Pb sulfide mineralization generally is associated with lower basin-margin carbonate horizons within the evaporite formations. Cu-ore mineralization is typical of clayey and sandy horizons at the base of these formations. They may also occur in beds that incorporate these formations or separate them. Carbonate horizons of evaporite formations may contain layers, enriched in celestite (occasionally with barite), fluorite and Mn-compounds. The most varied mineral development, including ore minerals, occurs in K-rich formations. For this reason follows a more detailed description of the basic characteristics of mineral genesis, especially as they are found in these formations.

TYPES AND MINERAL GENESIS OF THE MAIN K-BEARING FORMATIONS WORLDWIDE

Categories of K-bearing formation were distinguished on the basis of the mineral matter in K–Mg salt deposits. The categories are related to specific salt accumulation and deposition of sulfate, carbonate and terrigenous matter in these salt basins. The lithological peculiarities of different types of potassium-rich sections, in turn, established irregularities in ore- and nonore mineralization patterns of these assemblages. These were shown by examples of specific K-rich formations worldwide in various types and subtypes [10]. Three subtypes were identified among K-rich formations: the sylvinite-halite, carnallite-sylvinite-halite and bischofite (tachyhydrite)-carnallite-sylvinite-halite groups [11].

Chloride-Type Potassium-Rich Deposits

These deposits are most common and best known in sections of almost all Phanerozoic intervals between the Cambrian and Neogene. Section of the salt horizons are simpler and relatively uniform. Similarities are striking in comparing formations between various regions. Differences between stratigraphic sections of the three subtypes related mainly to the duration of salt deposition and thickness of K-bearing formations.

Sylvinite-Halite Subtype. The rare, K-rich formations of this subgroup are usually thin and of small areal distribution. The Paleogene K-salt formations of the Upper Rhine Graben belong here. These deposits fill the Upper Rhine Basin, the northern sector of the Rhine-Liv rift zone. The salt beds are underlain by Upper Eocene limestones, dolomites and dolomitic marls. The K-rich formations are of Sannoisian, Lower oligocene age. These contain three rock salt beds, with dolomite layers and marl strata. In upward direction, the unit thicknesses are maximum 200, 230, and 100 m, respectively. The beds are underlain, separated and overlain by a 80-350 m thick green marl sequence with dolomite, anhydrite and rock salt layers. The upper salt bed includes two sylvinite layers. The 1-6-m-thick sylvinite beds (lower unit) are separated by a 20-25-m-thick rock salt interval.

Pb, Zn, Cu, Ag, and Co ore mineral concentrations occur northeast of the Odenwald Graben in Tertiary deposits with barite veins.

Bitumen and occasional gas concentrations are known from the subsalt deposits in salt mines.

Carnallite-Sylvinite-Halite Subtype of K-Rich Formations. This subtype includes large K-rich units in the former USSR and abroad. They are of Lower Cambrian, Middle and Upper Devonian, Lower Permian, Triassic, Upper Jurassic and oligocene age. In the former USSR, the deposits include K-rich Lower Cambrian Siberian Platform formations, deposits of the Famennian Pripyat Basin, the Kungurian of Pre-Ural Basin and Upper Jurassic deposits of Central Asia. Abroad, significant deposits include Middle Devonian units of Canada, Triassic north African and Early Oligocene units in Spain. The presence of sylvinite and carnallite rocks is typical, as are also the mixed sylvinite-carnallite rocks. However, the relationship in these sections was most varied between sylvinites and carnallite rocks. Formations with a greater sylvinite content than in carnallite rocks, usually contain more clay rocks and fewer carbonate beds. The clay content is greater in salt rocks. Increased Br and Rb trace element content occurs only in carnallite rocks. Formations that contain more Br and Rb-bearing carnallite rocks than sylvinites and with a clay content lower than in anhydrite and carbonate beds, are characterized by celestite, barite and fluorite mineralizations in anhydrite and carbonate beds. The presence of native sulfur and Pb–Zn-sulfide mineralizations was established in marginal anhydrite-carbonate lithocomplexes of this subgroup that generally trap hydrocarbons.

A good example for mineral genesis in this subgroup is the K-rich Late Jurassic Gaurdak Formation interval in Central Asia. The section contains the following sequence (upward in the section): carbonate-anhydrite, salt and gypsum-anhydrite beds. The salt rock is characterized by underlying hard salt beds and K-salts. Three K-rich horizons occur in the K-salt interval. In the lower horizon, upward in the sequence, sylvinite lenses alternate with carnallite-sylvinite beds. At higher levels, sylvinites occur. The middle and upper K-rich horizons are represented, at lower levels, by sylvinite lenses and beds; at upper levels by carnallites. The thickness of K–Mg salts ranges from few m to 23 m. The salt mineral assemblage is quite simple and consists essentially of halite, sylvite and carnallite. An increase in the K content and in the thickness of K-rich formation from NE toward the SW occurs in the Akbash-Tyubegatan-Gaurdak and Kugitang-Karabil'-Karlyuk regions. The carnallite ratio concurrently increases in the sylvinite beds.

Seven anhydrite intervals, 10-80 m thick, have been identified, locally including dolomite beds in the salt unit. Salt rocks of the formation are depleted in Br; even carnallite rocks contain only 0.01-0.07% Br. The Rb content does not exceed 0.005-0.017%.

Large native sulfur deposits have been found in the lower, potassium-rich Gaurdak carbonate-anhydrite unit. The sulfur deposits occur in the carbonate horizon, along the cataclastic crush zone and flanks of erosional valleys. The sulfur ores are rich and include celestite (occasionally a maximum of 6%), chalcedony and some fluorite. Larger concentrations of celestite occur at the bottom of evaporite formation at the contact with the underlying Gissarsk carbonate formations. The middle portion of a 85-cm-thick celestite-bearing horizon is cemented by barite and fluorite. The celestite content, 20-25%, occasionally reaches 80%.

Celestite-barite, limonitized barite, fluorite-barite, rarely quartz-fluorite veins occur in the Gissarsk carbonate formation beneath the salt, in limbs of the Gaurdak and Gissarsk anticlines. Polymetallic ore mineralization is associated with Kugitang barite veins. Barite and galena forms the apex of veins; at lower levels, mostly sphalerite and calcite occur. These veins extend from the Gissarsk carbonate deposits into gypsum beds of the Gaurdak evaporate formation. Reef carbonate rocks that acted as hydrochemical barrier, also contain polymetallic stratiform ore deposits in the layers.

The Lower Cretaceous Gaurdak-Kugitang redbed deposits beneath the salt sequence consist of Upper Jurassic and Lower Cretaceous evaporite formations. They include three Cu-bearing horizons. In the main ore mineralization chalcopryrite, bornite and chalcocite as the major ore minerals.

Sylvinite and carnallite alone represent the K-rich Famennian formations of the Pripyat Basin and the Kungurian of the Upper Kama Basin. The K-Mg salts contain only sylvinite and carnallite. Sylvinite only dominate in the Pripyat Basin. A higher B content is typical of K-Mg salt of these formations. In the carnallite-bearing Famennian formations Br reaches 0.187%; in Horizon O₇, 0.42%. The Rb content in the carnallite-rich rocks is 0.02%; 0.08% in Horizon O₇. In Kungurian carbonate units of the upper Kama Basin and Bashkiria, certain horizons are enriched in celestite and fluorite. Celestite-bearing, Ba-celestite and sulfide (sphalerite and chalcopryrite) mineralizations occur in deposits that overlie K-rich Famennian salt units in the Pripyat Basin. Copper mineralization (chalcocite, to lesser extent, bornite and chalcopryrite; less covellite and cuprite) developed in the Pre-Ural Basin. It occurs in Upper Permian gray sandstones of the Solikamsk and Sheshminsk horizons that overlie the Kungurian evaporite formations.

In terms of mineral genesis, the carnallite, sylvinite-halite subgroup is important among K-rich evaporite formations abroad. K-rich sylvinite horizons are more common than are carnallite rich rocks in the Middle Devonian Prairie Formation of Canada. Even sylvinite and especially carnallite rocks, that contain greater amounts not only of Br but also Rb, are mined. Sylvinite probably formed from carnallite.

The Prairie Formation is under- and overlain by carbonate rocks. A barrier reef bounds the evaporite basin on the northwest. The reef consists of porous Pine Point dolomites. The K-content of the formation increases southeastward. K-Mg salt deposits occur in the Saskatchewan and Williston subbasins. Sharp vertical and horizontal changes are typical of the red sylvinite beds. Localized sylvinite replacement of the carnallite rock and further depletion of K-beds takes place by their replacement by halite rock. The replacement zones are associated with fracture lineaments in the basement. The faults had conducted Cl-Na solutions toward the surface.

The evaporite formation in the Edmonton-Calgary region of Alberta shields sulfur-bearing oil and gas deposits. Three-quarters of Canada's native sulfur supply is derived the S-bearing natural gases. A large hydrogen sulfide deposit was opened up NW of Edmonton. Here, the native S content in the sulfur ore reaches 90%.

The Pine Point barrier is associated with an area that includes about forty Pb-Zn ore bodies with a mean 2.4% Pb and 6% Zn content. Sulfur concentrations range between a few hundred thousand to 15 million tons. A maximum 30-m-thick dolomite biostrome, south of the reef extends to some distance into the evaporite beds [14]. About half of these deposits occur in porous, cavernous Preskill dolomites; in the upper part of the barrier reef where ores are richer. Pb-Zn were transported in chloride complexes in chloride solution to the barrier ore deposition zones along the northern, main and southern faults. They collected with hydrogen sulfide along a hydrochemical barrier that formed stratiform- and vein deposits of galena, sphalerite, with minor amounts of marcasite and pyrite.

Bischofite (Tachyhydrite)-Carnallite-Sylvinite K-Evaporite Subgroup. This category is exclusively represented by Aptian (Lower Cretaceous) formations of Brazil, west Africa, and Thailand. The most complete sections of these formations in the Congo Basin are maximum 900 m thick. Maximum ten cycles include K-rich beds. K-Mg salts in the cycles commonly contain 20-25-m-thick carnallite units, locally replaced by sylvinite. Two-to-three units occur in the

lower cycles, eight-to-nine in the upper ones. In addition to carnallite rocks, beds in the upper section contain tachyhydrite-, rarely, bischofite-bearing rocks, with a total thickness of maximum 30 m. Greater Br- and B-concentrations occur in the tachyhydrate rocks. They also include minor amounts of Zn, Pb, Cu, and Mn. Source brines generally are rich in these components.

North of the Congo Basin (Krousou) along the fault that frames the Gabon Basin on the east, the Lower Cretaceous sandstone cement includes Pb-compounds, also galena and pyrite veins, with minor amounts of sphalerite, smithsonite, chalcopyrite and barite [15].

South of the Congo Basin, near Losto, Angola, Lower Aptian gypsum-bearing carbonate layers display Zn mineralization, with minor amounts of Pb compounds and asphalt-type hydrocarbons. Barite and Mn-rich limestone layers occur further south, in the Aptian Mozambique Basin gypsum deposits. Lateral correlatives of Aptian evaporites (Upper Kuvo beds) in the Sel Massif also include minor amounts of Pb-compounds.

This type of K-evaporite has not been found in our country. They may occur in Central Asian Lower Cretaceous evaporite beds. The studied deposits are thin in the studied sections.

Sulfate-Chloride Evaporite Formations. This group includes mostly Permian formations in this country and abroad. They occur in the Kungurian (Lower Permian) Dnieper-Donets Basin, in the Precaspian Syncline, in Late Permian Zechstein beds in West Europe and in the Salado Formation, USA. In the following, the most typical mineral formations, the Zechstein and Kungurian deposits, are reviewed in two areas.

The maximum 2-km-thick Kungurian potassium-rich formations in the Precaspian Syncline and the south Pre Ural Basin display 10-13 evaporite cycles. In the five lower cycles the K salt beds contain polyhalite rocks. Even sylvinites, kieserite and polyhalite beds occur in the upper section. Beds of the upper five cycles are represented by sylvinites, carnallite- and bischofite-rich rocks.

Peripheral salt-free, and salt-rich interior lithocomplexes occupy the formations' distribution area. From the basin periphery toward the center, the sulfate-carbonate terrigenous complex along the Ural margin alternates with gypsum rocks. Along the platform-margin the complex alternates with carbonates, then dolomite-anhydrite and gypsum-anhydrite rocks. The salt lithocomplex displays a well established succession toward the basin center. On the west and northwest, halite starts the sequence; on the north, polyhalite and halite; on the southwest, locally thenardite-halite that farther away changes to sylvinite-halite (locally kieserite), still farther, carnallite-halite occur. Finally, bischofite-carnallite-sylvinite-halite lithocomplexes developed in the northwest and central basin areas. The last two lithocomplexes in the Inder, Satimol, Matenkoz, Ozankah, Svetlyi Yar, and other areas contain fewer kainite and langbeinite-bearing rocks.

The K-rich formations of the Precaspian region contain a collection of K-Mg rocks that form a complex mineral assemblage. Carnallite and bischofite rocks are enriched in Br (maximum 0.3-0.5%); the carnallite rocks also in Rb (maximum 0.026%). Salt rocks contain B. As the result, commercial deposits of residual borate here formed in salt cupola cap rocks. This B content is typical of rock types of K-rich formations. The B content is greater in polyhalite-kieserite-sylvinite-bearing and carnallite-sylvinite rocks and greatest in kieserite-sylvinite-bischofite-carnallite rocks (mean 4.94% B content). Kaliborite, respectively boracite, dominates in borites of these rocks. In horizons of Basalts, the B_2O_3 content is 1.5-9.0%; in metric samples and lumps, locally 18-26%. The greater B content in the horizon is associated with carnallite- and bischofite-bearing lithocomplexes the Precaspian Syncline.

Celestite, barite, fluorite mineralization is associated with dolomite anhydrites of the Filipovsk Horizon at the base of the Kungursk K-rich formations and caprocks of salt cupolas in synclines. It is also associated with dolomites of subsalt Upper Artinsk deposits of the Precaspian region. Celestites and barite-celestites sometimes represent 20-25% of the volume of rocks in which maximum 0.3-m-thick celestite lenses and veins (maximum 0.8 m) occur. Fluorite occurs in minor amounts in Kungur Mts. area evaporite formations in the main anhydrite horizons, and in B and K-beds. Northward, in the Pre-Ural Basin in the Kungur city area a higher fluorite content is related to the Tyuisk carbonate units (maximum 8-30% fluorite) between salt beds.

Carbonate-anhydrite rocks of the Filippovsk Horizons of the Kungursk evaporite formation and in the subsalt Upper Artinsk carbonate rocks in this region contain native S as irregularly distributed mottles and inclusions. The marginal salt-free anhydrite-carbonate lithocomplex of these formations and carbonate-gypsum caprocks of salt cupola structures locally display greater sulfur concentrations.

The Podgornensk native sulfur unit in the peripheral Kungurian Pre-Ural lithocomplex at the town of Aktyubinsk occurs in sulfur deposit of secondary carbonate rocks, within layered gypsum and anhydrite beds. The sulfur deposit often also intersects gypsum and anhydrite beds. In the ores the mean native sulfur content is 10-15%, locally 25%. Celestite,

occasionally barite veins and geodes, also traces of pyrite and hauerite occur in a maximum 15 thick sulfur deposit, defined by E-W faults.

The carbonate units above the gypsum cap rock of the salt cupolas in the Precaspian regions (Matenkons, Satimol, Dzhamantau, etc.) contain disseminated native sulfur, sulfur crystals, nests, and veins. Its average concentrations in maximum 0.7-m-thick units did not exceed 5-10%. Carbonate rocks in the cap rocks displayed pyritization and galena (at the town of Novobogatinsk) and sphalerite inclusions.

The Ultuelyakhsk Mn-ore deposit occurs north of the Precaspian region, in the Bashkirian Preural area. It is located in the peripheral anhydrite-carbonate lithocomplex of the Kungurian evaporite formation.

In western Europe, salt-bearing lithocomplexes of K-rich Zechstein-age formations are maximum 1-2-km-thick in the North German and central Poland basins. In interior uplifts and marginal zones, these formations alternate with carbonate-anhydrite and carbonate lithocomplexes; locally, in a coastal zone with terrigenous beds. Four-five evaporite cycles occur in complete salt lithocomplex sections with the following horizons: clays, dolomite, anhydrite and rock salt, with K-Mg-salt layers. The evaporite distribution pattern; lithocomplexes and thickness value was determined by the flank tectonics of the basement and the subsalt rock sequence.

The K-Mg salt beds are composed mostly of carnallite rocks, sylvinite and kieserite and hard salt. A succession of carnallite rocks, hard salt, sylvinite and, finally, halite toward the basin margin and interior uplifts. Certain geologists consider this a primary, facies change; others the result of secondary change, due to mineral replacement. Polyhalite, tachyhydrite (bischofite-), langbeinite and kainite-bearing rocks are less widespread. Vanthoffite, loewite, and glauberite minerals are even scarcer. K-Mg salt beds are associated with the four lower cycles of the formation. Their thickness varies between 3-15 m. The value is greater in thickened intervals.

An increased Br, Rb, occasionally Li and Cs concentration occurs in the carnallite-bearing of the Zechstein Formation. Various salt rocks of the formation contain Br. Rocks of the carbonate horizons include native S, celestite, barite and fluorite, sulfide-polymetallic and copper mineralizations.

The B, in the carnallite rocks reaches a few tenths of one percent. This value is somewhat lower in sylvinites and hard salt.

Rb content in carnallite rocks ranges between 0.005-0.06%. Recrystallized carnallite rocks are richest in Rb. Smaller amounts of Rb occasionally occur in kainite, langbeinite and sylvite.

Li occurs in the insoluble residue of Zechstein-age salt rocks and salt-bearing rocks and salty clays (0.001-0.1%). Cs was also established in certain carnallite rocks (maximum 0.0002%).

Significant B concentrations in Germany's Zechstein Formation are associated with carnallite-bearing, hard salt, and kainitic rocks in the second cycle beneath the Stassfurt cycle. Boracite concretions (20-25 cm) are associated with dispersed or developing kieserite mineral. Boracite nests may reach 1.4-ton weight. Danburite, strontiohilgardite, strontioginorite, paraveatchite, luneburgite and sellaite also occur in the anhydritic hard salt. Radial hydroboracite nodules occur in rock salt of the Stassfurt cycle near the contact with anhydrite and polyhalite.

Native sulfur, celestite, barite and fluorite have long been known from anhydrite-carbonate horizons of Zechstein evaporite formations in western Europe. However, only in 1957 have native sulfur deposits been discovered in Emsland, western Germany. Celestite lenses, extending 500 m laterally, 1-30-m thick, occur mostly in dolomites of the lower part of the Zechstein interval at Gipshagen, Helmscheid and oberhembeck, south Westphalia. They also occur at Hessen and Stassfurt. In certain beds the celestite concentration reaches 90%. A Ba-celestite paragenesis with ankerite and siderite occurs in the Zechstein dolomites and limestones of Thuringia. The barite content is greater in the peripheral portions of these horizons. Layered, light-colored barite and small amount of celestite occur at the base of the Stassfurt cycle in northwest Germany between the main dolomite and basal anhydrite.

The F-content of Zechstein formation is associated with the main (Z_2) and mottled (Z_3) dolomites. In the first horizon, the fluorite is represented as crystals, druses and pore fillings in secretions. The 3-4-m-thick fluorite-bearing beds include fluorite lenses and beds in the second horizon, with the fluorite content occasionally reaching 95%. Fluorite occurs as fine grains and concretions. Fluorite crystals occupy empty pore spaces and fractures. Minor amounts of native S, celestite, barite, sellaite, lead and zinc occur in fluorite-bearing dolomites.

Copper (copper-shales) and Pb-Zn mineralizations are associated with thin underlying carbonate-terrigenous units of Zechstein evaporite formations. They occur along the southern margin of the formations from Great Britain, across Germany to Poland. Lower Zechstein dolomitized limestones and underlying black Darchem marls in northern England

contain mostly galena and pyrite ore minerals. The Pb content is usually 1.2-1.3%, occasionally 4%. The Cu and Zn mineralization is much less significant (Zn content: maximum 4%). Mo and Ni admixtures also occur.

The Mansfeld Basin copper schists include carbonates (maximum 30%) and bitumens (10%). Ore mineralization, as veins and layers is represented by Cu-, Zn-, and Pb-sulfides. Zonal development marks the section: Cu occurs at the bottom, Pb, at higher levels, followed even higher by Zn. Bornite, chalcocite, chalcopyrite, and covellite are the main copper minerals. Widespread Zn mineralization (sphalerite, smithsonite), with galena, pyrite and barite characterizes the overlying Zechstein limestones.

In the Polish Lubin-Gloguv deposits, the Cu-content of the Zechstein marls and the Morist Cu mineralization also alternate with Pb mineralization; farther away, with Zn mineralization, with traces of gypsum. In addition to chalcopurite, the bornite content increases upward in the section; later the chalcocite, finally the chalcopyrite content becomes significant. Pb-Zn ore mineralization occurs in the upper units; a few percentages (locally, 10-20%) of Pb occur in galena-bearing layers.

Sulfate Subgroup of K-Rich Formations. These are rare and probably typical only of the Miocene formations of the Precarpathian Basin (Romania and the Ukraine), as well as of Sicily. Early and Middle Miocene Lower Molasse beds in the Precarpathian Basin are associated with the Lower and Upper Vorotyshchensk and, Upper Stebnik K-rich formations. In the Upper Molasse, the evaporite-bearing Tirassk Formation is located in the outer basin zone. Certain geologists consider the Upper Stebnik and Tirassk Formations time-correlatives in various structural zones of the Basin.

The K-rich formations of the Precarpathian zones are under- and overlain by terrigenous rocks. They contain salt-rich clays, clayey salts; less often, beds of pure rock salt. They contain sandstone and sandstone-argillite breccia beds with various amounts of salt content. The terrigenous matter, supplied by the Carpathians, played an important role in K-rich formation intervals and even in salt rocks. With sole exception of beds in the underlying Lower Vorotyshchensk Formation, only single and usually thin anhydrite beds occur. The most complete sections in the Tirassk evaporite formation in the outer basin margin zones include rock salt, anhydrites (gypsum) and carbonate rocks. The thickness of the K-bearing formations ranges between 300-1000 m, that of the evaporitic Tirassk Formation, between 15-350 m.

K-Mg salts in the Vorotyshchensk K-bearing formations contain mostly kainitic, langbeinite-kainitic and langbeinite rocks; also mixed-composition, hard rock-type deposits. Generally, kainitic and langbeinite-kainite rock, locally sylvinite lenses occur in the K-rich Upper Stebnik deposits. The beds are a few meters to 50 m thick, occasionally thicker. Sylvinite lenses are generally 5-12 m thick.

Mirabilite and glaserite-rich rocks and mineralized water horizons formed in the hypergenetic zone under K-Mg-sulfate salt beds.

Due to the high clay content, the Br, B, and Rb concentrations usually are low in Precarpathian K-Mg salts. A relatively high (maximum 0.14%) Br content occurs in sylvinites. More often, the concentration is only one hundredth of one percent.

As the subsalt deposits of the Precarpathian Basin include oil and combustible natural gas horizons, the K-rich Lower Vorotyshchensk formation and intraformational deposits of the Zagorsk Suite contain ozokerite, asphalt and kir (solidified petroleum). Minor sulfur shows with galena and sphalerite (brunckite) inclusions occur in a thick anhydrite bed below this formation. Cu-mineralization is present in intraformational Lower Stebin deposits.

The Tirassk evaporite formation in the outer basin zone contains a halite-anhydrite-carbonate rock complex. It probably is the marginal lithofacies of the K-bearing Upper Stebin Formation. Native sulfur and polymetallic ore mineralization with galena and sphalerite (brunckite), occur in the intraformation Zagorsk (Dobrobovsk) unit.

A halite-anhydrite-carbonate complex, probable marginal lithofacies of K-rich Upper Stebnik formations, is associated with a native sulfur deposit in the outer zone of the basin that contains the Tirassk evaporite formation. The rocks occur in the suture zone between the basin's outer belt and the Russian Platform. S-ores contain 20-25% native sulfur.

Two, 0.1-1.0-m-thick layers of celestite-carbonate rocks, with maximum 45% celestite content and small amounts of barite occur in carbonate rocks of this formation.

LITERATURE CITED

1. G. A. Belenitskaya, "Facies and paleotectonic models of evaporite systems and certain questions of their ore content," *Ores in Sedimentary Complexes* [in Russian], Nedra, Leningrad (1989), pp. 30-40.
2. V. I. Berger and V. P. Feoktistov, "Geodynamic types of ore-bearing sedimentary basins," *Problems of Stratiform Deposits* [in Russian], Vol. 1 (abstracts), Chita (1990), pp. 12-14.
3. L. G. Bogasheva, "The role of salt basins in the development of stratiform deposits," *Geol. Rudn. Mestorozhd.*, No. 3, 18-29 (1987).
4. G. Yu. Butuzova and N. L. Lisitsyna, "Metal content of deep water Red Sea basin deposits," *Litol. Polezn. Iskop.*, No. 3, 6-32 (1983).
5. D. I. Gordzhevskii, A. A. Kartsev, D. I. Pavlov, et al., *Metal and Petroleum Paragenesis in Sediment Beds of Hydrocarbon-Bearing Basins* [in Russian], Nedra, Moscow (1990).
6. B. V. Dolishnii, "Hydrothermal ore mineralization in rock salt the Dnepropetrovsk-Donets Basin," *Mineral. Sb.*, No. 43, 1, 87-90 (1989).
7. V. I. Kityk, "Evaporites and associated mineral resources," *Geology and Geochemistry of Combustible Resources*, No. 61, 49-55 (1983).
8. S. M. Korenevskii, *Complex Mineral Resources of Evaporite Formations* [in Russian], Nedra, Moscow (1973).
9. S. M. Korenevskii, "Ore content of evaporite formations and enclosing formations," *Litol. Polezn. Iskop.*, No. 3, 109-113 (1984).
10. S. M. Korenevskii, *Pattern of Zonal Distribution of K-Rich Lithocomplexes. New Data on Salt Basin Geology, USSR* [in Russian], Nauka, Moscow (1986), pp. 3-9.
11. S. M. Korenevskii, "Lithology of K-rich formations," *Litol. Polezn. Iskop.*, No. 2, 66-82 (1990).
12. D. V. Rundquist (ed.); *Criteria for Regional Evaluation of Solid Mineral Resources* [in Russian], Nedra, Leningrad (1978).
13. V. P. Parnachev, "The role of evaporite cementation in the formation of stratiform barite and polymetallic deposits, western slope of the South Ural," *Problems of Stratiform Deposits* [in Russian], Part 2 (abstracts), Chita (1990), pp. 67-68.
14. W. R. Barager, "Geology of lead-zinc deposits on Pine Point," *West. Miner.*, **39**, No. 7, 52-54 (1966).
15. J. Gaio, "Paleogeographical and sedimentological control of copper, lead, and zinc mineralizations in the Lower Cretaceous sandstones of Africa," *Econ. Geol.*, **71**, No. 3, 409-422 (1976).
16. C. F. Davidson, "Some genetic relationships between ore deposits and evaporites," *Bull. Inst. Mining and Metallurgy, Sect. B*, **75**, 216-225 (1966).
17. A. R. Renfro, "Genesis of evaporite-associated stratiform metalliferous deposits," *Econ. Geol.*, **69**, No. 1, 33-45 (1974).

TEXTURE OF COARSE-CLASTIC ALLUVIUM OF THE BELAYA RIVER

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With respect to grain-size composition, three types of sediments were distinguished: boulder-pebble, gravel-pebble, and sandy-gravel, representing different combinations of six main subdistributions of clastic particles. Polymodality of the fragments' distribution curves, association of subdistributions, and a deep deficit of particles at the boundary of the gravel and sandy grades were shown. The role of the tectonic factor in altering the texture of sediments in various sections of the valley was noted.

This article is devoted to study of the texture of coarse-clastic sediments of a mountain-plains river, using the results of fractional grain-size analysis. As the object of investigation, we chose channel alluvium of the Belaya River (a tributary of the Kama). The authors set themselves the following tasks: to deepen ideas about the texture of coarse-clastic alluvium on the basis of data from fractional grain-size analysis, systematize curves of the fractional grain-size composition of sediments, establish the dependence of the alluvium's fractional grain size on the tectonic and geomorphological situation of sedimentation, and reveal additional quantitative indices of transformation of the texture of sediments downstream, from mountains to plains.

These and many other problems have been solved by lithologists with the use of ordinary grain-size analysis on the example of many rivers. As a result, a system of ideas has been developed about the texture of coarse-clastic alluvium [7, 14, 18]. A fairly complete summary of works on this theme is given in V. G. Chernov's bibliographic reference book [17].

Researchers have given special attention to such questions as the difference in grain size of mountain and plains alluvium, the change in texture of sediments downstream, etc. One of the most common patterns of change in grain-size composition of alluvium along a river valley is the direct dependence of the size of fragments on the slope and flow rate of water, and a decrease in their average size [1, 4, 6, etc.]. An increase has been noted in the degree of rounding of pebble material from mountains to plains, especially in the first kilometers of transportation [2, 10, 15]. A great many particular patterns have also been established. Thus, on the basis of quantitative calculations for alluvium of rivers of the Fergana depression, N. N. Berzilin [3] showed a general reduction in volumes of clastic material of medium- and coarse-pebble size in the direction from the mountains to the plain. A dependence of the average diameter of alluvial fragments on the width of river valleys' bottom, the ratio of rocks of different petrographic compositions in source provinces, the effect of tributaries [1], and the activity of tectonic structures [7] was revealed. L. B. Rukhin [14] noted an increase in the average size of grains of the sandy component of coarse-clastic alluvium (filler) in the plains section of a river in comparison with the mountain one. A. A. Chistyakov [18] observed a sharp difference in texture of the gravel-sandy filler of boulder-pebble sediments of the Zeravshan River in different sections of branched channels.

Study of the texture of alluvium using fractional grain-size analysis was begun comparatively recently [8, 9, 19]. These investigations are laborious and, thus far, have not become common. Nonetheless, fundamentally new possibilities of detailed analysis of the composition and texture of alluvial sediments have been discovered.

The first results of study of fractional grain size of pebble alluvial sediments made it possible to develop an idea of their texture on the basis of concepts of heterogeneity and maturity. On the example of alluvium of the Kuban River, a rise in the degree of sorting of grains of sandy filler of coarse-clastic alluvium was established from the mountains to the plain [8]. Gently sloping and polymodal distribution curves of the filler's particles, which are typical of mountain and foothills sections of the river, are replaced by single-modal, sharp-peaked ones with the transition to the plains zone. Subsequently, in studying the grain-size composition of coarse-clastic sediments of various rivers of the USSR (Dnestr, Vilyui, Pechora,

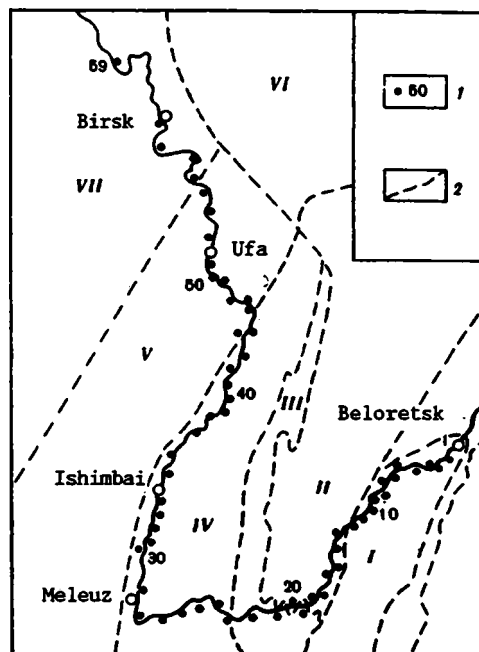


Fig. 1. Tectonic structure of the region of investigations and places where samples were taken in the Belaya River valley: I) Zilyaro-Emba megasynclinalorium; II) Bashkir megaanticlinorium; III) Western Ural outer zone of folding; IV) Bel'skaya megadepression; V) Southeast slope of Volga-Ural antecline; VI) Kama-Bashkir megaarch; VII) Upper Kama megadepression; 1) place where a sample was taken and its number; 2) boundaries of tectonic structures.

Onega, Don, and tributaries of the Irtysh, Tom, and Kama), additional peculiarities of the texture of alluvium within the bounds of different tectonic and geomorphological zones were established [9]. The origin and gradual deepening of the deficit of clastic particles at the boundary of gravel and sandy grades were noted as one of the most important traits of change in the texture of coarse-clastic alluvium with the transition from mountains to plains. Another characteristic trait is transformation of the polymodal distribution curve of fragments to bimodal. At the same time, common features of the texture of coarse-clastic alluvium were clearly manifested: polymodality of distribution curves, poor sorting, heterogeneity, etc., which significantly distinguishes them from sandy and silty sediments. H. Ibbeken [19] investigated the fractional grain size of sediments near the mouth of mountain rivers of Italy. In most cases, he found a bimodal distribution of clastic material, with a deficit of grains ~ 2 mm in size. Fragments of the gravel-pebble part of the sediments are primarily governed by Rosin's distribution; and sandy grains, by a lognormal distribution.

All of the preceding works based on fractional grain-size analysis of alluvium either encompassed small sections of the valleys of various rivers, or only concerned the sandy part (filler). The purpose of the present article is to study the fractional grain size of alluvium of one fairly large river practically over its whole extent, including mountain, foothills, and plains sections.

INVESTIGATION PROCEDURE

Samples (total number 59) were taken from contemporary coarse-clastic alluvium of the channel-shoal facies of the Belaya River in the section from Beloretsk to Dyurtyuli, ~ 900 km long (Fig. 1). Sampling was done by digging pits in the head parts of bars.

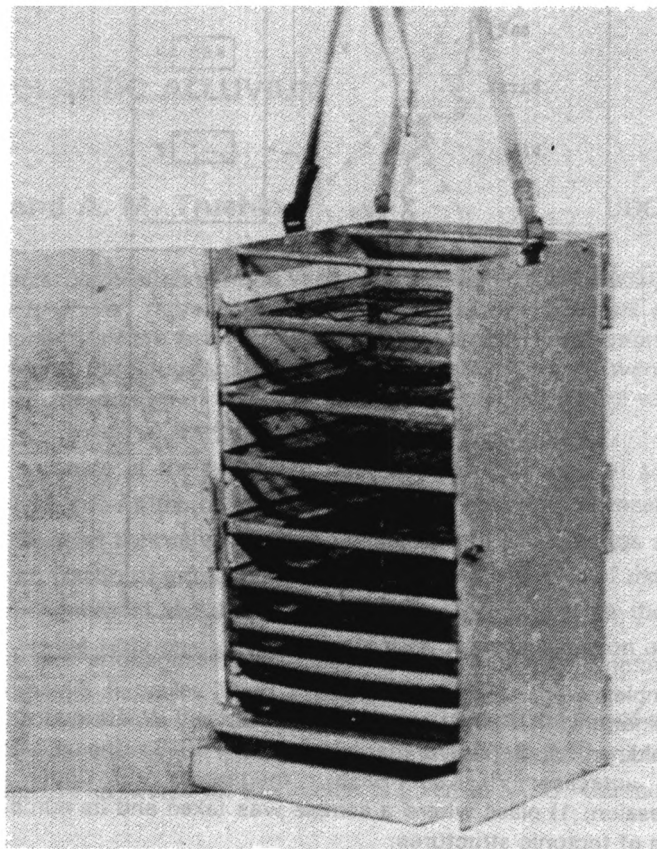


Fig. 2. Field sieve for fractional grain-size analysis of coarse-clastic alluvium.

The initial samples were separated in field conditions on a special sieve constructed by A. M. Trushin (Fig. 2), into the following classes, mm: >40 , 40-31.5, 31.5-25, 25-20, 20-16, 16-12.5, 12.5-10, 10-8, 8-6.3, 6.3-5, and <5 . Clastic material was loaded into the sieve in portions of 10 kg each. The weight of the sample varied from 67 to 210 kg, depending on the maximum size of the fragments. Fragments more than 40 mm in size were classified with the help of wire loops. In this case, the following classes were additionally distinguished, mm: >100 , 100-80, 80-63, 63-50, and 50-40. The sieve's screens, as well as the loops, had a square mesh. All of the classes were weighed on a spring balance with accuracy to within 0.1 kg. From the material <5 mm in size, we took an average sample weighing 1-2 kg for subsequent investigation in the laboratory. The morphology of fragments of several narrow size classes was evaluated on the basis of measurements of three cross sections (for 25-100 fragments of each class).

In laboratory conditions, we elutriated silt and clay particles (<0.05 mm). Coarser material was sifted on a fractional set of sieves, with separation into the following classes, mm: 5-4, 4-3.15, 3.15-2.5, 2.5-2, 2-1.6, 1.6-1.25, 1.25-1, 1-0.8, 0.8-0.63, 0.63-0.5, 0.5-0.4, 0.4-0.315, 0.315-0.25, 0.25-0.2, 0.2-0.16, 0.16-0.125, 0.125-0.1, 0.1-0.08, 0.08-0.063, and 0.063-0.05. Thus, in the interval from 100 to 0.05 mm, clastic material was separated into 33 fractions in accordance with Baturin's granulometric γ -scale.

Classification of fragments larger than 100 mm into grain-size fractions will give a reliable result only with a significant increase in the weight of the sample, in accordance with Richards' and Chechott's formula [11]. In this case, the laboriousness and length of field investigations rises sharply, which is clearly inexpedient. Particles <0.05 mm were also not subjected to analysis, due to their small content in the sediment (usually $<1\%$).

According to the results of field and laboratory investigations, we calculated the alluvium's overall grain-size composition. In processing the data, we used an "Iskra-226" personal computer.

GEOLOGICAL AND TECTONIC-GEOMORPHOLOGICAL STRUCTURE OF THE BELAYA RIVER VALLEY

In the river valley, a diverse complex of rocks is being eroded. In the mountain section below Beloretsk, cross sections are represented by Ordovician, Silurian, and Devonian rocks, primarily terrigenous and carbonate: conglomerates, gritstones, sandstones, siltstones, shales, dolomites, and limestones. Further downstream, in the region of the mouths of the Kaga and Avzyan rivers, the valley is cut into rocks of the Upper Proterozoic: conglomerates, quartz sandstones, siltstones, mudstones, limestones, and dolomites. Still further downstream, also within the bounds of the mountain section, the river valley once again cuts through a terrigenous-carbonate complex of Paleozoic rocks (Ordovician, Silurian, Devonian, Carboniferous). In the foothills and plains territory, Permian rocks are widespread: sandy-clay formations with interlayers of gritstones and conglomerates, clay limestones, etc. In the plains section, among the source rocks a noticeable role is played by Cenozoic terrigenous formations (alluvial terraces and other genetic types of deposits). In the river basin, tributaries also erode magmatic rocks, primarily of ultrabasic composition [16]. Thus, a predominance of terrigenous rocks in the feed sources, and the widespread occurrence of conglomerates and gritstones among them are favorable prerequisites for formation of thick strata of coarse-clastic alluvium of the Belaya River, which largely inherits peculiarities of the eroded rocks' texture.

Tectonically, the river valley is confined to three main structures: the folded Urals, the Cisural marginal trough, and the eastern part of the Russian platform. Within the bounds of the folded Urals, three tectonic zones are distinguished, which the river cuts across in succession: the Zilyaro-Emba megasynclorium, the southern end of the Bashkir megaanticlinorium, and the Western Ural outer zone of folding. The foothill section of the valley is mostly confined to the Bel'skaya megadepression; and the plains section, to the southeastern slope of the Volga-Ural antecline and the Upper Kama megadepression (see Fig. 1). Geomorphological features of the valley's structure indicate the activity of tectonic blocks in different stages of geological history, including neotectonic. Neotectonic movements in the river valley were manifested rather contrastingly. The total rise of the Earth's crust during the neotectonic stage exceeds 300 m in the mountain section of the valley; in the foothills and plain it is 100-200 m. On maps of the latest tectonic movements of the USSR compiled under the editorship of N. I. Nikolaev (1959 and 1977), within the mountain section of the valley, in the segment from Beloretsk to the mouth of the Avzyan River, a zone of relative neotectonic subsidence is distinguished, where the total rise was less than 200 m. The presence of recent fractures in the mountain section indicates neotectonic activity of blocks of various orders. For example, a series of recent fractures accompanies the southern end of the Bashkir megaanticlinorium. In the foothills, a zone of relative subsidence is noted (in the section from Meleuz to the mouth of the Sim River), where the total rise of the Earth's crust in the neotectonic stage was less than 100 m.

On the map of neotectonics of the Southern Cisural given in A. P. Rozhdestvenskii's work [12], in the foothills and plain the total rise in the neotectonic stage is from 100 to 200 m, with the exception of the section from Ishimbai to the mouth of the Sim River, and also the part of the valley near the river's mouth, where this rise does not exceed 100 m.

The universal relative rise of territory of the Southern Cisural in the contemporary stage can be judged from results of repeated leveling along the Kuibyshev-Chelyabinsk railroad line, with the minimum rate of contemporary rise being noted within the bounds of the Bel'skaya megadepression (0.8 mm/yr). Results of repeated leveling confirm that the nature of contemporary movements of the Earth's crust is inherited from ancient tectonic structures.

For rivers of the Belaya River's basin, a clear dependence of the channels' slopes on neotectonics has been established: within the bounds of positive morphostructures the slopes are increased; in negative ones they are reduced [12]. This also determines the dependence of the grain-size composition of coarse-clastic alluvium on the territory's tectonic structure.

GENERAL FEATURES OF THE TEXTURE OF COARSE-CLASTIC ALLUVIUM

The most general feature of the texture of coarse-clastic alluvium of the Belaya River is polymodality of the distribution curves of clastic material. This is seen as a manifestation of heterogeneity of the alluvium, which is a mixture of a number of sets of clastic particles (subdistributions). Each subdistribution of fragments is connected with certain feed sources, is differently transported by the water flow and deposited in the sediment, and occupies different positions in the volume of the alluvial layer, in accordance with the packing effect [9, 21].

TABLE 1. Characteristics of Basic Subdistributions of Clastic Particles of Alluvium of the Belaya River

Subdistribution	Fraction	Mode, mm	Portion in sediment, % (limits of values)	Roundness	Petrographic composition
a	Boulder, coarse-pebble	80-63 or 63-50	0-30	Slight or medium	Quartzites, effusives, sandstones
b	Medium-pebble	40-31.5 or 31.5-25	0-35	Medium	Quartzites, effusives, schists, sandstones, quartz
c	Fine-pebble	20-16 or 16-12.5	2-35	Medium or high	Schists, quartz, quartzites, effusives, limestones, sandstones, gneisses, amphibolites
d	Coarse-gravel	8-6.3	8-28	Medium	Quartz, schists, quartzites, effusives, limestones
e	Medium-gravel	4-3.15	6-23	Medium or slight	Quartz, quartzites, limestones, schists, effusives
f	Coarse- and medium-sandy	From 1-0.8 to 0.315-0.25	5-50	The same	Quartz, feldspars, micas

Transport of bottom sediments in the Belaya River valley, as in the valleys of other, analogous rivers, is accomplished within the bounds of a continuous, moving, or active, layer [4]. This form of transport of clastic material is favorable for formation of a texture of the sediment based on a coarse-clastic framework. The role of the latter is performed by the subdistribution of the largest fragments. In the active layer of bottom sediments, fragments of smaller sizes move in the intervals between large fragments; their size corresponds to the pore diameter of the coarse-clastic framework. In the sediment formed, they make up the second subdistribution of fragments with respect to size, etc. High turbulence of the flow, which is manifested in its eddy structure, also promotes transport of fine-clastic material in the composition of bottom sediments. During the period of receding floodwater, smaller and smaller particles occupy free spaces in the sediment. In the final analysis, a polymodal structure of the coarse-clastic alluvium is formed.

In different sections of the river, in accordance with the flow rate, the degree of its turbulence and thickness of the active layer change. In this case, the role of the framework in the sediment can be performed by subdistributions of finer fragments. With still lower flow rates, the amount of coarse fragments in bottom sediments proves to be insufficient for formation of a framework. A distinctive "inversion" of the sediment's texture occurs: coarse fragments are irregularly strewn in the mass of finer (sandy and gravel) particles.

The main role in formation of coarse-clastic alluvium of the Belaya River is played by fragments of six subdistributions: three pebble, two gravel, and one sandy (Table 1). Besides that, in the alluvium of the river's mountain section there is a subdistribution confined to the boulder part of the granulometric spectrum. However, since the content of fragments more than 100 mm in size was evaluated cumulatively, it does not seem possible to give a sufficiently complete characterization of the boulder subdistribution.

In the structure of coarse-clastic alluvium of the Belaya River, the same peculiarity is noted as has been established for channel sediments of many rivers: the modes of basic subdistributions are usually separated by the same interval, which is equal to 3γ [9]. Therefore, they are confined to classes the dimensions of which constitute a sequence divisible by two, mm: 80-63, 40-31, 20-16, etc. The fine-gravel part of the granulometric spectrum is an exception, to which a subdistribution of grains is also confined, but the latter does not play a noticeable role in the composition of alluvium.

In formation of the texture of coarse-clastic alluvium, a certain quantitative ratio (association) is maintained between subdistributions. This association is especially clearly revealed in comparing the contents of fragments of modal classes of the basic subdistributions (Table 2). As a rule, a successive reduction is observed in the content of fragments from the maximum mode to the adjacent modal classes. This peculiarity, on the one hand, is a result of the regulating

TABLE 2. Contents of Fragments in Modal Classes of Basic Subdistributions of Alluvium, %

Sample No.	Subdistribution					
	a	b	c	d	e	f
Mountain sections of the Belaya River						
2	—	10,0	11,7	6,5	3,1	1,6
4	—	7,9	9,6	5,9	3,3	1,5
5	—	8,4	6,2	5,4	5,4	3,4
8	—	4,9	10,6	8,6	4,3	2,5
12	8,2	9,9	4,3	3,1	2,4	2,3
13	6,1	8,1	5,5	3,8	2,5	3,9
14	—	12,7	6,2	3,4	2,4	4,7
15	7,8	9,5	4,6	4,0	2,7	3,1
16	9,9	4,8	3,3	3,1	2,4	2,4
17	3,6	5,1	5,3	3,2	1,8	2,4
18	8,6	7,2	5,7	4,6	3,7	2,4
19	7,1	7,2	6,3	5,1	3,4	2,8
21	—	8,9	8,5	4,4	4,4	4,4
22	—	9,5	9,0	3,6	1,4	4,7
23	—	11,5	6,2	3,5	1,6	1,8
24	5,7	6,6	6,0	4,7	3,5	3,2
25	—	9,0	6,9	4,3	3,3	2,7
Foothills sections of the Belaya River						
27	—	—	11,1	4,7	3,7	3,0
29	—	7,9	6,7	5,8	3,3	2,9
31	—	7,0	6,1	10,3	6,3	2,4
32	—	11,7	8,0	4,7	1,8	2,4
33	—	8,5	7,2	4,3	3,2	2,9
34	—	9,8	13,2	7,2	2,8	0,2
35	—	10,7	13,3	4,4	3,1	2,0
36	—	8,7	6,7	5,3	2,7	6,3
37	—	4,9	9,5	7,7	4,2	6,0
38	—	—	10,0	8,8	5,1	10,1
39	—	7,8	10,5	4,7	2,6	5,5
40	—	—	9,3	9,5	6,7	3,7

role of the water's flow rate and, on the other, is connected with manifestation of the packing effect when fragments drop out into the sediment. Deviations are noticeable for sandy particles (subdistribution *f*), which for the most part are deposited in the concluding stage of sedimentation, during the recession of floodwater, and fill the pores between fragments of the coarse-clastic framework.

A characteristic feature of the texture of coarse-clastic alluvium of the Belaya River in the foothills and plain is a deep deficit of clastic particles at the boundary of the gravel and sandy grades. In analyzing the curves of grain-size composition of sediments, the presence of two types of deficits of fragments is established. For the most part, they correspond to the junctions of subdistributions. For example, the most consistent position on the granulometric scale is occupied by deficits confined to the following classes, mm: 63-50, 25-20, 12.5-10, and 5-4. Deficits of this type, as a rule are not very deep and encompass a comparatively narrow part of the granulometric spectrum (usually 1 γ). On the average, the content of particles in the deficient, narrow-grade class is $\approx$ 50% less than the content of fragments in adjacent modal classes.

The deficit of grains at the boundary of the gravel and sandy grades is distinguished by a number of significant traits. First of all, it is considerably deeper. In the deepest part of the deficit, the content of fragments of the narrow-grade class is reduced to 0.2% in one of the samples, and in none of them does it exceed 3.3%. These contents are 10 times less than the modal values for the adjacent subdistribution *f*. Secondly, this deficit is significantly wider and usually occupies an interval of the granulometric scale from 2.5 to 0.63 mm, i.e., 6 γ . The deepest part of the deficit is most often confined to the following narrow-grade classes, mm: 2.5-2, 1.6-1.25, and 1-0.8. The deficit under consideration is clearly manifested on a histogram of the maximum contents of fragments in narrow-grade classes.

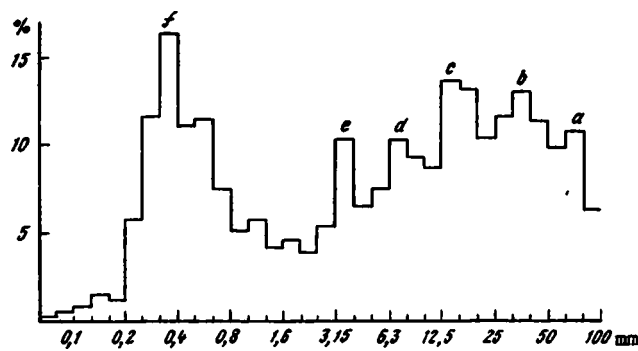


Fig. 3. Histogram of maximum contents of clastic particles in narrow-grade classes (*a*, *b*, *c*, *d*, *e*, *f* – in this and following figures, subdistributions of clastic particles).

The problem of formation of a deficit at the boundary of the gravel and sandy grades in terrigenous sediments and, in particular, in alluvium has been widely discussed by lithologists for many years. A very wide range of opinions has been expressed: from acceptance of the universal nature of this deficit to complete denial of it. Scientists defending the former point of view usually discover a deficit of clastic grains in the interval from 4 to 1 mm [13, 14, 19, 22, 23, 25]. The reasons for its formation are believed to be a difference in the forms of transport of gravel fragments and sandy grains in a river channel, instability of grains of the fine-gravel grade during transportation, peculiarities of the mechanical destruction of bedrocks in the process of the physical weathering, etc. Another group of scientists considers the deficit as a result of the combination of different methods of grain-size analysis, or the effect of the grains' shape on data from sieve sizing [20]. Finally, some researchers did not find a deficit of grains near 1 mm at all, in spite of the use of fractional grain-size analysis [24].

The results of our investigations of the texture of coarse-clastic alluvium of the Belaya River confirm the reality of the deficit at the boundary of the gravel and sandy grades. At the same time, it is not noted in all analyses, which explains why a number of scientists did not find it. The fact is that the deficit of grains at the junction of the gravel and sandy grades is a regular result of transformation of the texture of coarse-clastic alluvium during transport of clastic material downstream in a river, from mountains to plains. The appearance of this deficit, from our point of view, is primarily due to mechanical instability of fine-gravel and coarse-sandy grains during transport, since a significant portion of them is made up of rock fragments and concretions. Moreover, the gravel fraction in alluvial situations is subjected to the strongest biochemical weathering [5]. Finally, a definite role is played by the composition of the source rocks, the texture of which is inherited by the alluvium. Specific data on alluvium of the Belaya River will be given below.

TYPES OF COARSE-CLASTIC ALLUVIUM

Taking into account the ratio of subdistributions, we can distinguish three types of coarse-clastic sediments of the channel-shoal facies of alluvium of the Belaya River (Fig. 4).

Boulder-pebble sediments are mostly composed of fragments of subdistributions *a* and *b*. The subdistribution of boulder fragments is also present. This type of alluvium is characterized by a progressive decrease in the portion of subdistributions from coarse- to fine-clastic and, accordingly, a reduction in the contents of fragments in modal classes from coarse to fine. Boulder-pebble sediments are typical of sections of mountain relief, in which an intensive contemporary rise of the Earth's crust is observed, and the slope of the water surface is increasing.

Gravel-pebble sediments consist primarily of fragments of subdistributions *b*, *c*, *d*, and *e* in various combinations; subdistribution *a* is seldom present. Subdistributions *b*, *c*, or *d* may be predominant in the sediments, depending on peculiarities of the tectonic and geomorphological situation, which determine the water flow's hydrological regime. Gravel-pebble sediments are the most common type of coarse-clastic alluvium of the Belaya River's channel-shoal facies. They are characteristic of various sections of the valley (mountain, foothills, and plains).

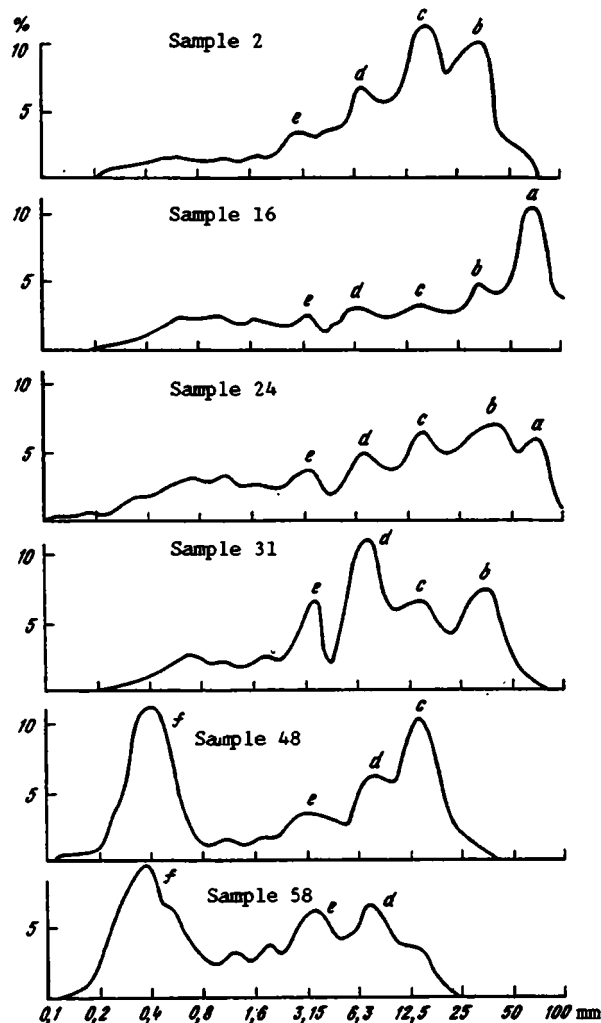


Fig. 4. Typical distribution curves of clastic alluvial material of the Belaya River. See Fig. 3 for conventional notations.

Gravel-sandy sediments include clastic grains of subdistributions d, e, and f, with a predominance of the latter. An admixture of fragments of subdistribution c is possible in small amounts. Gravel-sandy sediments, usually with an admixture of occasional pebbles, are found only in the plains section of the valley.

EFFECT OF THE TECTONIC SITUATION ON THE TEXTURE OF ALLUVIUM

Contemporary tectonic activity of blocks of the Earth's crust shows up most noticeably in the grain-size composition of mountain alluvium of the Belaya River. Taking into account the size and textural peculiarities of alluvium, the mountain section can be divided into three zones.

The upstream zone (from Beloretsk to the mouth of the Avzyan River) is confined to the Zilyaro-Emba megasynclorium. In connection with the fact that the block confined to this zone is experiencing relative subsidence, the grain-size composition of the alluvium is distinguished by the following peculiarities. Subdistributions b and c are predominant in the sediment, and, in some cases, d. Fragments of subdistribution a and boulders are practically absent in alluvium of the channel-shoal facies. The portion of fragments more than 50 mm in size does not exceed 6.5%, and the average size varies in the range of 11-21 mm.

The middle zone (from the mouth of the Avzyan River to the mouth of the Irgizla River) encompasses the section of the valley directly adjacent to the Bashkir megaanticlinorium. Thanks to active contemporary rise of the corresponding block of the Earth's crust, the rate of water flow in the channel is increasing. Sediments of channel shoals are mostly composed of fragments of subdistributions *a* and *b*; subdistribution *c* is predominant only in isolated samples. Boulders are constantly present on bars (up to 30%). The content of fragments larger than 50 mm in size varies from 15 to 45%, and the average size of fragments of the channel-shoal alluvium is from 26 to 53 mm.

The downstream zone (from the mouth of the Irgizla River to the village of Yalchina), which ends the mountain section of the valley, is confined to the Western Ural outer zone of folding. This block is experiencing relatively slight contemporary uplift. Here, the alluvium is composed mainly of the same subdistributions, but subdistribution *b* is predominant among them. The boulder content does not exceed 10%; fragments larger than 50 mm amount to 5 to 25%. The average size of alluvial fragments of the channel-shoal facies varies from 19 to 35 mm.

In the foothills and on the plain, less contrasting changes in the size and texture of alluvium are observed in individual sections of the valley, which is explained by less contemporary activity of the Earth's crust. A certain coarsening of clastic material occurs in zones cutting across local positive structures. As an example, we can give the zone of the Ishimbaev uplift. In this zone, which is experiencing inherited contemporary rise of the Earth's crust, a general coarsening of alluvium is observed. Fragments more than 80 mm in size appear in the amount of 0.6%, while upstream all the way to Meleuz they are absent in channel-shoal sediments. The content of fragments more than 50 mm in size reaches 11%; upstream they are no more than 8%. The modal class of subdistribution *b*, which is predominant in the sediment, shifts in the direction of a coarser narrow-grade class (50-40 mm). The average size of fragments rises to 16-24 mm; upstream it varies in the range from 11 to 18 mm. In sections where the river cuts across local negative structures, the portion of coarse-pebble fragments in the sediments is sharply reduced, and in the medium-pebble part of the granulometric spectrum the mode shifts to the finest class (31.5-25 mm). The average size of alluvial fragments is reduced to 5 mm or less.

CHANGES IN TEXTURAL CHARACTERISTICS OF ALLUVIUM FROM MOUNTAINS TO PLAINS

Average Size of Fragments. The trend of decreasing average size of fragments of the channel-shoal facies downstream in the Belaya River is manifested fairly clearly, but it is significantly complicated by inhomogeneity of the territory's tectonic structure (Fig. 5a).

The maximum average size of alluvial fragments is noted in the mountain section and is 53 mm; the minimum, 1.5 mm, is in the river's lower course (according to particular data). It should be kept in mind that, in the lower reaches, river bars are primarily sandy, and coarse-clastic alluvium is found sporadically on a limited number of shoals.

The average grain size of the filler of coarse-clastic alluvium (particles 1-0.05 mm in size) also decreases downstream, although not as noticeably. The average value of this index is 0.55 mm for the mountain section, and 0.40 mm for the plains section (see Fig. 5b). This result contradicts L. B. Rukhin's data [14]. In the mountains and foothills, the maximum mode for filler grains is usually confined to the narrow-grade class of 0.8-0.63 mm; on the plain, to the classes of 0.63-0.5 and 0.4-0.315 mm.

Sorting. It has been suggested that the coefficient of relative entropy H_r be used as a measure of the degree of sorting of grains by size for sediments with polymodal distribution curves [13]. Coarse-clastic sediments of the Belaya River's channel-shoal facies are characterized by values of H_r in the range of 0.77-0.92. Thus, they are classified as unsorted and absolutely unsorted. No trend of change in the value of H_r is noted downstream (see Fig. 5c). Lack of sorting of the river's coarse-clastic sediments is one of the characteristic consequences of their heterogeneity. In turn, the heterogeneity of alluvium is determined by inconstancy of the water flow's hydrological regime during the floodwater period, the diversity of feed sources of alluvium, and by the rate of contemporary movements of the Earth's crust, which activate erosion processes.

The distribution curves for filler grains in mountain alluvium are comparatively gently sloped, single-modal or polymodal; in the plains section they are more often single-modal. The degree of sorting of filler grains is lowest in the foothills (S_0 averages 1.4), and approximately the same in alluvium of the mountains and plain: for the mountain section

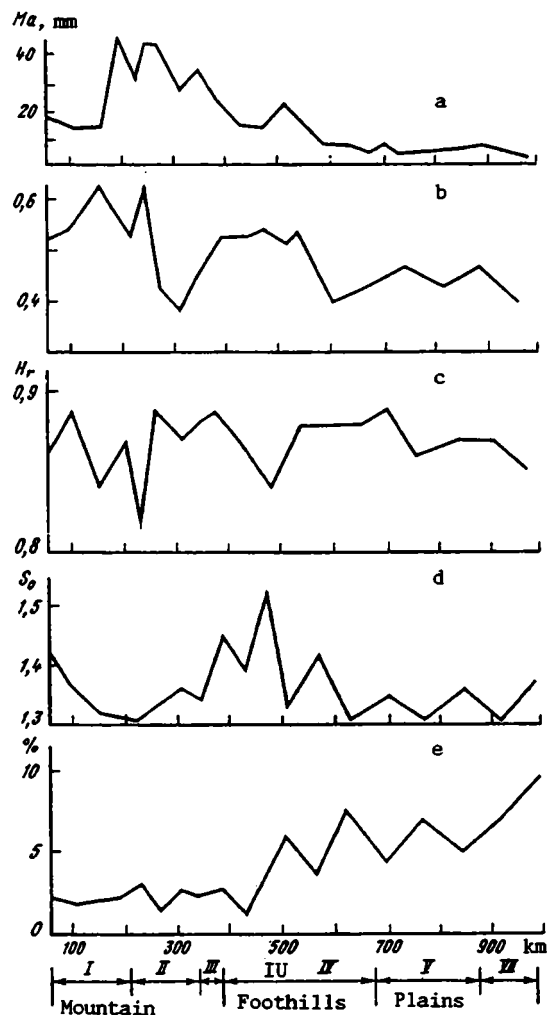


Fig. 5. Changes in textural characteristics of sediments downstream in the Belaya River (according to average data). a) average size of fragments; b) average size of filler grains; c) coefficient of normalized entropy; d) coefficient of sorting of filler grains; e) difference in contents of clastic particles in the modal class of subdistribution f and in the class corresponding to the deepest part of the deficit; I-VII) tectonic structures (see Fig. 1); IU - Ishimbaev uplift.

S_0 averages 1.35; and on the plain, 1.33. We can draw a conclusion about an insignificant rise in the degree of sorting of filler grains in plains coarse-clastic alluvium in comparison with the analogous index for the mountain and foothills sections (see Fig. 5d).

Morphology of Fragments. The shape of pebble fragments of the Belaya River's alluvium is diverse and depends on their size, feed sources, petrographic composition, time of transportation, and other factors. The ratio between the main morphological groups of fragments changes in different narrow-grade classes. For fragments of one class, this ratio is variable in different sections of the valley.

A general trend was established in changes in the fragments' morphology with respect to grain-size fractions: from coarse classes to fine, the portion of isometric varieties increases and the portion of flattened ones decreases (Table 3).

Downstream in the river, in each class the portion of flattened and isometric fragments rises, although this trend is not equally manifested for fragments of different sizes (Table 4). Besides that, the degree of flattening and elongation of pebbles decreases downstream. For example, in the narrow-grade class of 31.5-25 mm, in the section near the mouth of

TABLE 3. Ratio of Pebbles of Different Shapes in Alluvium of the Belaya River (Class 31.5-25 mm), %

Sample number	Morphology of pebbles			
	flattened	isometric	elongated	tabular
1	30	—	22	48
7	38	—	20	42
14	24	—	14	62
19	24	2	16	58
24	26	4	28	42
39	54	4	15	27

Remark. Sample 39 is from the foothills section of the valley; the rest of the samples are from the mountain section.

TABLE 4. Ratios of Pebbles of Different Shapes in Modal Classes of Basic Subdistributions of Alluvium of the Belaya River in Foothills, %

Subdis-tribution	Class, mm	Morphology of pebbles			
		isometric	flattened	elongated	tabular
b	31,5-25	4	54	15	27
c	16-12,5	4	43	33	20
d	8-6,3	10	20	31	39

the Kana River (mountain zone) the average degree of flattening of pebbles of the corresponding morphological group is equal to 1:8, while below Sterlitamak (foothills) it is 1:5. The greatest length of pebbles of that narrow-grade class in the mountain section is 104 mm; and in the foothills section, 65 mm.

Deficit of Fine-Gravel—Coarse-Sandy Grains. The presence of a deficit at the boundary of the sandy and gravel grades of grains in individual samples has already been noted in the mountain section. Here, it is appreciably different from other deficits marking the junctions of subdistributions of fragments, however it still does not reach the parameters typical of plains alluvium. It has a comparatively small width of (3-4) γ and moderate depth (the difference between the content of grains in the deepest part of the deficit and in the modal class of the adjacent subdistribution f does not exceed 4.5%). It should be emphasized that, in the mountain section of the valley, this deficit is only discovered in the alluvium of lithofacies characterized by weakened dynamics of the water flow and is most likely inherited from the terrigenous source rocks.

From the middle of the foothills section (below Sterlitamak), the deficit at the boundary of the gravel and sandy grades is found in all varieties of alluvium, without exception. From this point and further downstream, the width and depth of the deficit gradually increase (see Fig. 5e). For example, in the lower reaches of the river the width of the deficit in individual samples reaches 8 γ , and the excess of the mode of subdistribution f over the deepest part of the deficit is 15%.

Maturity of Alluvium. The maturity of coarse-clastic alluvium is determined, first of all, by the type of distribution curve (poly- or bimodal), and by the depth and width of the deficit of grains at the boundary of the gravel and sandy grades [9]. In particular, sediments with a high degree of maturity are characterized by a bimodal distribution curve and by a deep deficit of fine-gravel—coarse-sandy grains. Besides that, the degree of rounding of clastic material and its morphology must be taken into account.

Downstream in the Belaya River, the maturity of coarse-clastic alluvium gradually rises. This is manifested in a decrease in the number of basic subdistributions of fragments (from 6 to 3), an increase in the content of fragments in modal classes, deepening and widening of the deficit of grains at the boundary of the gravel and sandy grades, a rise in the degree of rounding of clastic material, and an increase in the portion of fragments with flattened and isometric shapes.

However, with respect to the degree of maturity, coarse-clastic alluvium of the Belaya River's plains section differs significantly from typical plains alluvium. Thus, in the river valley no sandy-gravel-pebble sediments with a high degree of maturity and a characteristic bimodal distribution curve were found at all. The fairly low degree of maturity of coarse-clastic plains alluvium in the Belaya River is probably due to the proximity of mountain structures and the corresponding texture of source rocks.

1. The main characteristics of the texture of coarse-clastic alluvium of the Belaya River, established according to results of fractional grain-size analysis, are polymodality of the distribution curves of clastic material, association of the quantitative content of subdistributions of fragments, the presence of a deep deficit of grains at the boundary of the gravel and sandy grade, a low degree of maturity, and slight sorting of fragments by size.

2. The basic types of coarse clastic sediments of the channel-shoal facies (boulder-gravel, gravel-pebble, and sandy-gravel) differ significantly in their ratio of the fragments' subdistributions.

3. A large role in changes in the alluvium's texture in different sections of the valley is played by the tectonic factor. The coarsest alluvium is observed in the section directly adjacent to the Bashkir megaanticlinorium, where intensive ascending movements of the Earth's crust are recorded.

4. Downstream in the river, from mountains to plains, the average size of fragments decreases significantly, in accordance with replacement of boulder-pebble sediments by gravel-sandy ones; the deficit of fine-gravel—coarse-sandy grains widens and deepens; the alluvium's maturity rises to a certain extent; and the portion of isometric and flattened fragments increases.

LITERATURE CITED

1. K. M. Berkovich, L. F. Litvin, R. V. Lodina, and E. I. Sakharova, "Formation of material composition of mountain rivers' alluvium (on the example of Western Transcaucasia)," in: *Formation of Placers in River Valleys* [in Russian], Moscow Univ. (1980), pp. 29-35.
2. O. A. Borsuk, "Changes in characteristics of alluvium in rivers of different orders," in: *Formation of Placers in River Valleys* [in Russian], Moscow Univ. (1980), pp. 35-38.
3. N. N. Verzilin, "Changes in petrographic composition and amount of pebble material downstream in modern rivers of the Fergana valley," in: *Alluvium* [in Russian], Perm Univ. (1976), pp. 3-12.
4. V. N. Goncharov, *Principles of Dynamics of River Flows* [in Russian], Gidrometeoizdat, Leningrad (1954).
5. N. G. Dobrovolskaya, "Interrelation of mechanical abrasion and underwater biochemical weathering of alluvium in mountain rivers," in: *Theses of Reports to the III All-Union Conference "Dynamics and Thermics of Rivers, Reservoirs and Marginal Seas"* [in Russian], Vol. 1, Moscow (1989), pp. 190-191.
6. Yu. A. Ibad-Zade, *Movement of Sediments in Open Channels* [in Russian], Stroiizdat, Moscow (1974).
7. B. S. Lunev, *Differentiation of Sediments in Contemporary Alluvium* [in Russian], Perm Univ. (1967).
8. B. M. Osovetskii, "Material composition of contemporary alluvium of the Kuban River and conditions of its formation," *Litol. Polezn. Iskop.*, No. 1, 66-80 (1977).
9. B. M. Osovetskii, "Structure of coarse-clastic alluvium according to data from fractional grain-size analysis," *Litol. Polezn. Iskop.*, No. 1, 67-77 (1982).
10. N. V. Razumikhin, *Paleogeographic and Hydrological Principles of Formation of Alluvial Placers* [in Russian], Leningrad Univ. (1982).
11. V. V. Revin, *Quaternary Sands and Sandy-Gravel Deposits* [in Russian], Nedra, Moscow (1977).
12. A. P. Rozhdestvenskii, *Neotectonics and Development of the Relief of the Southern Ural Region* [in Russian], Nauka, Moscow (1971).
13. S. I. Romanovskii, *Sedimentological Principles of Lithology* [in Russian], Nedra, Leningrad (1977).
14. L. B. Rukhin, "Patterns of formation of grain-size composition of river sands," *Nauch. Byul. Leningr. Gos. Univ.*, No. 19, 39-41 (1947).
15. E. I. Sakharova and N. V. Lebedeva, "Factors determining the composition of alluvium of the Mzymta River," *Litol. Polezn. Iskop.*, No. 1, 97-110 (1967).
16. Yu. D. Smirnov and N. P. Borovko, *Geology and Paleogeography of the West Slope of the Urals* [in Russian], Nedra, Leningrad (1977).

17. V. G. Chernov, Psephites (Bibliographic Reference Book) [in Russian], Moscow Univ. (1986).
18. A. A. Chistyakov, Mountain Alluvium [in Russian], Nedra, Moscow (1978).
19. H. Ibbeken, "Jointed source rock and fluvial gravels controlled by Rosin's law: a grain-size study in Calabria, South Italy," J. Sediment. Petrol., **53**, No. 4, 1213-1231 (1983).
20. S. K. Kennedy, T. P. Meloy, and T. E. Durney, "Sieve data — size and shape information," J. Sediment. Petrol., **55**, No. 3, 356-360 (1985).
21. A. J. Moss, "Bed-load sediments," Sedimentology, **18**, No. 34, 159-219 (1972).
22. F. J. Pettijohn, Sedimentary Rocks, Second ed., Harper, New York (1957).
23. R. J. Russel, "Where most grains of very coarse sand and fine gravel are deposited," Sedimentology, **14**, No. 11, 31-38 (1968).
24. J. H. Shea, "Difficiencies of clastic particles of certain sizes," J. Sediment. Petrol., **44**, No. 4, 985-1003 (1974).
25. D. W. Spencer, "The interpretation of grain size distribution curves of clastic sediments," J. Sediment. Petrol., **33**, No. 1, 180-190 (1963).

PETROCHEMICAL EVOLUTION OF THE ARCHEAN CONTINENTAL CRUST

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We discuss the general patterns of the petrochemical evolution of the Archean continental crust. We show the incompatibility of evolutionary crust-forming trends with the trends of the principal magmatic formations of recent regions of growth in the continental crust. We establish the predominant role of intracrustal granitization and sedimentary-metamorphic differentiation in forming the sialic crust as opposed to the contribution of mantle magmatism. For the first time, the Aldan and Anabar shields are defined as evolutionary analogues in the early stages of crust formation; the Canadian and Ukrainian shields are proposed as examples of later stages.

Regular correlations of sediment accumulation and metallogeny and magmatic activity during the individual development stages of the continental crust have been studied based on comparisons of supply provinces and the specific composition of the typical igneous rocks in them [28, 29]. This analysis is most reliable for the top levels of differentiated granite-gneiss covers, where granitoids and other igneous rocks are clearly the primary source of material for sedimentary rocks. As one proceeds to study the deeper erosional cuts of shields with areas of increasingly older crust, meta-sedimentary rocks involved in ultrametamorphism and deep-crustal anatexis become primary sources for the granitoid type most common on continents (S-granites).

Isotopic and geochemical data show that the scale of recycling of crustal material increases sharply starting from the Late Archean. However, signs of inheritance of ancient matter by younger crustal complexes are also seen in the early stages of crust formation: in "gray gneiss" and other Early Archean complexes [1]. A general correlation between the composition of igneous and sedimentary (metasedimentary) rocks is observed in various stages of crust development [25, 26]. This means that sedimentation and magmatic processes are globally represented in crust formation by a common series of averaged (gross) compositions of successive continental crust forms. In this context, the types of principal sources of crustal material primary for Archean crust, which makes as much as three-quarters of the continents, are particularly important. Various theories on this debatable issue depend on the choice of proposed model of continent formation and, in the final analysis, reflect the different views of investigators as to the applicability of the current concept of plate tectonics to Precambrian processes.

This paper offers a new approach to this problem based on the method of evolutionary petrochemical alkalinity-calcinity trends of the magmatic series and crust-building formations proposed by the present author in recent years [5-8]. The present study is mainly concerned with two types of interrelated aspects of this problem: 1) the evolutionary sequence of the principal types of igneous and metasedimentary rocks, and 2) the petrochemical trends of typical crust-developing formations in conjunction with the evolution of the mean composition of their Archean crust as illustrated by a number of ancient shields (Canadian, Ukrainian, Aldan, and Anabar).

EVOLUTIONARY SEQUENCE OF THE PRINCIPAL TYPES OF SEDIMENTARY AND IGNEOUS ROCKS OF THE CONTINENTAL CRUST

Well-known studies by Ronov, Yaroshevskii, et al. have made considerable contributions to the analysis of the chemical evolution of the continental crust. These investigators brought together ample analytical data on the composition of the most common rock groups in the earth's crust: schists, granitoids, and basalts. It is reasonable to assume that, based on a comparison of the average composition for similar time intervals, it is possible to make judgments about the general trends in the evolution of the composition of the earth's crust [25].

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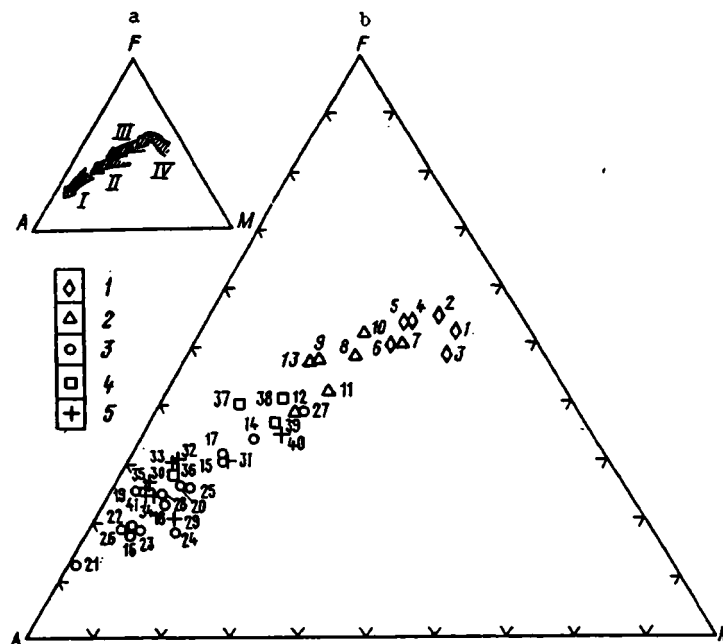


Fig. 1. Evolution of magmatic and metamorphic rocks on the AFM diagram: *a* — principal crust-forming rock groups [25]: I — granitoids, II — sandstones, III — schists, IV — basalts; *b* — representative types of Precambrian rocks and reference magmatite compositions: 1 — basalts, 2 — schists and graywackes, 3 — gray gneisses, 4 — enderbitoids and charnokites, 5 — granitoids. Numbers in the diagram: 1 — Archean tholeiites [30], 2 — basic Archean effusives [36], 3 — oceanic tholeiites [3], 4-6 — basalts (4 — PR₁, 5 — PR₂₋₃, 6 — Ph), 7-9 — schists (7 — AR₁, 8 — AR₂₋₃, 9 — PR₁ [25]), 10 — Archean argillites [36], 11 — average composition of the detrital component of the sedimentary Archean series [36], 12 — Lower Precambrian graywackes (Wyoming, USA) [21], 13 — metasedimentary rocks of the East European Platform [4], 14-26 — rocks of typical gray gneiss complexes outside Russia (14-16 — Labrador, 17-19 — Amitsok, 20,21 — Swaziland, 22-24 — Ontario, 25,26 — Scotland) [37], 27 — gray gneisses of Central Aldan [18], 28 — primary crustal granite (Kola Peninsula) [9], 29,30 — average composition of Archean tonalites and trondhjemites [30], 31-34 — average composition of Precambrian granitoids [25] (31 — AR₁, 32 — AR₂₋₃, 33 — PR₁, 34 — PR₂₋₃), 35 — Precambrian granite after Daley, 36,37 — charnokites [2] (36 — average global composition, 37 — average for 15 regions), 38 — enderbitoids of Central Aldan [26], 39 — enderbitoids of the East European Platform [17], 40 — tonalites of the cordilleras [35], 41 — average global granite [34].

Ronov and co-workers [25] compared the petrochemical composition of these rocks with the aid of the *AFM* diagram (A = sum of Na_2O and K_2O ; M = MgO ; F = FeO and Fe_2O_3). The compositions form a uniform trend on the diagram (see Fig. 1a): from basalts to clay schists and sandstones to granites. This trend is comparable to the trend of the differentiated calcareous-alkaline magmatic series. It was thus concluded that the common cause for the differentiation of matter in individual covers and in the continental crust as a whole was the evolution processes in the earth's interior which involved magmatic evolution of matter in the mantle.

Though the *AFM* diagram is generally used in the literature, it is best suited to comparisons of basaltoids, which are characterized by significant variations in the proportions of magnesium and iron. However, when comparing magmatic series, especially when one wishes to draw boundaries between granitoids and other final differentiates, the *AFM* diagram may be insufficient in a wide range of silicity [6]. The $(\text{Na} + \text{K})/\text{Ca} - A_c$ diagram can be much more effective for this purpose [4-8]. The basic parameter of this diagram (A_c) is more universal than SiO_2 or other differentiation indicators as it takes into account both the general basicity of igneous rocks (B_0) as a function of the concentration (Me) of all petrogenic cations, and their relative basicity (B_c): $A_c = 4\text{Si}/B_0$, where $B_0 = \Sigma(Me \times B_c)$. The value of B_c is estimated on a 10-point scale: from 1 for silicon to 9.5 for potassium.

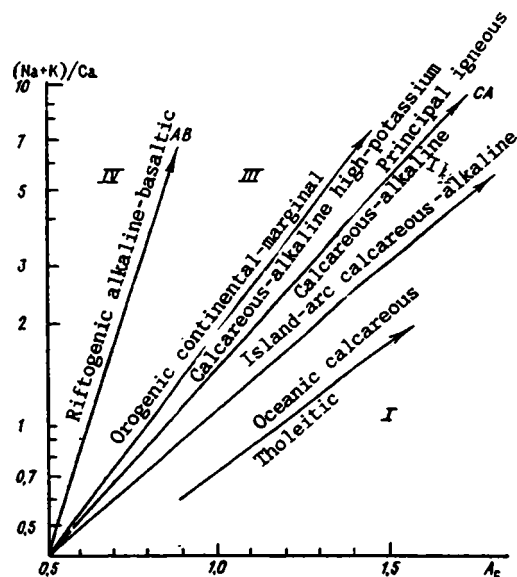


Fig 2. Reference petrochemical trends of igneous formations in the $(Na + K)/Ca - A_c$ diagram: I-IV - classification fields (I - calcareous, II - calcareous-alkaline, III - subalkaline, IV - alkaline).

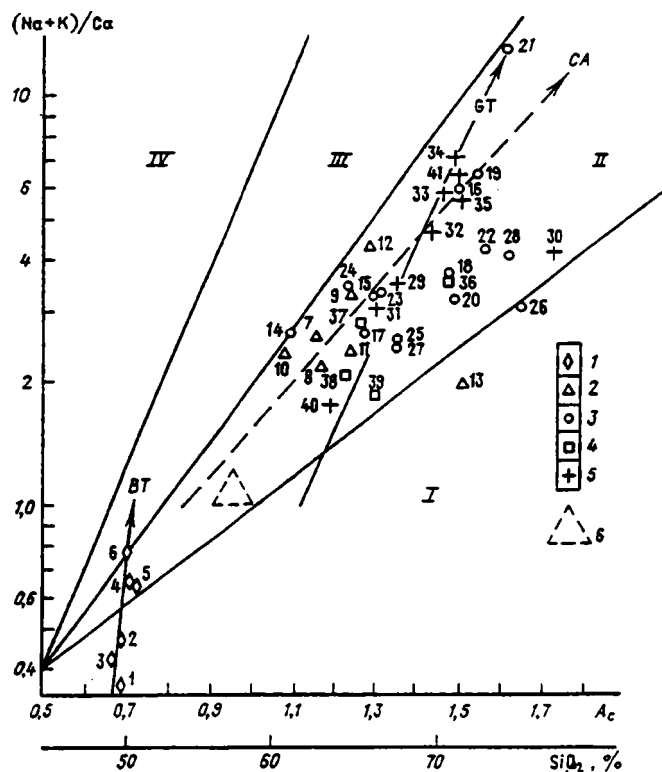
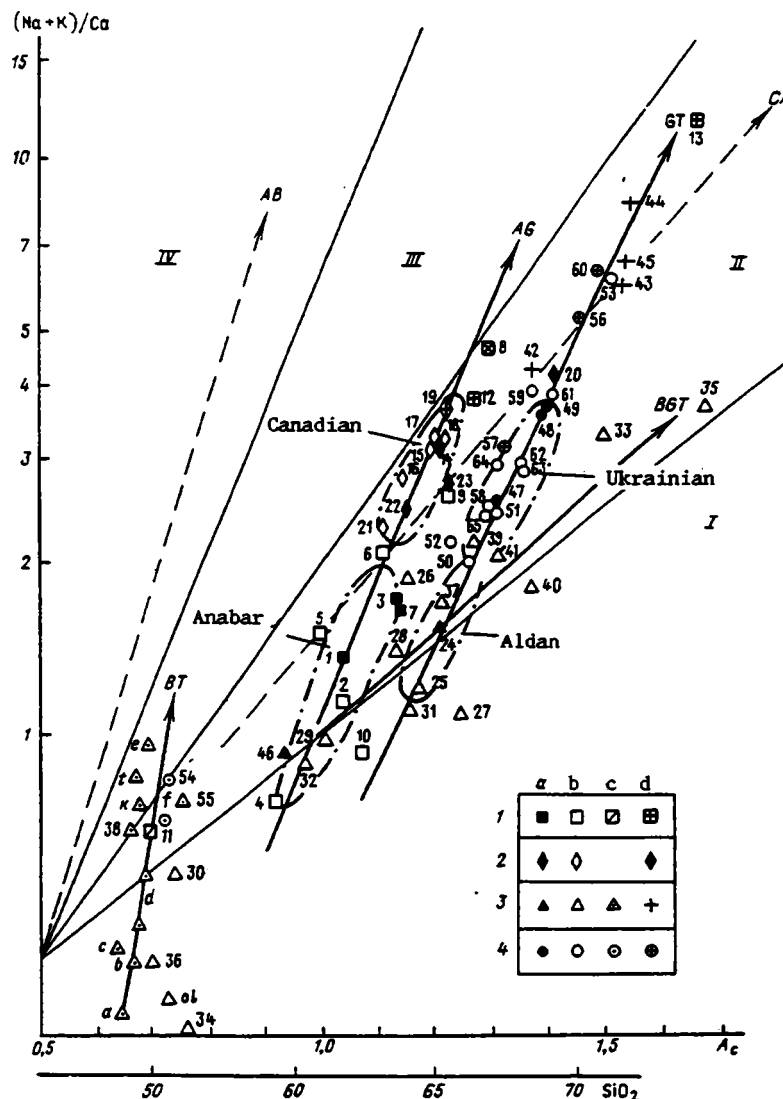


Fig. 3. Composition of principal types of igneous and metamorphic rocks on the $(Na + K)/Ca - A_c$ diagram: 1 - basalts, 2 - schists and graywackes, 3 - gray gneisses, 4 - enderbitoids and charnokites, 5 - granitoids, 6 - field of composition of andesites from Cenozoic, island arc, and continental-marginal provinces [35]. Numbers in the diagrams are as in Fig. 1b.



In contrast to the *AFM* diagram, the other parameter — $(Na + K)/Ca$ — makes it possible to directly estimate the ratio of alkalis to "lime" (CaO), which is the petrologic basis for the conventional classification of igneous rocks: subdivision into calcareous, calcareous-alkaline, and alkaline formations. Compared to gross alkalinity ($Na_2O + K_2O$), parameter $(Na + K)/Ca$ displays a much wider range (variability). In the series from basites to granites, $(Na_2O + K_2O)$ varies from 2.5 to 10%, i.e., by a factor of three or four, while $(Na + K)/Ca$ varies from 0.3 to 50 and more, i.e., by more than a factor of 100. This allows differentiating not only the principal types but any transitional types of igneous rocks and series according to their trends within the field of the diagram. The diagram is highly suitable for trend analysis, because the magmatic series in its coordinates correspond to a regular system (bundle) of linear trends rather than arbitrary curves (as in the *AFM* or Zavaritskii diagram). The bundle includes reference trends of igneous formations from the principal types of geodynamic settings (Fig. 2). We isolated the main calcareous-alkaline trend (*CA*) which characterizes the average composition of the most massive effusive formations of island arcs and continental margins [5].

Within the framework of this discussion, it is convenient to characterize evolutionary trends of Archean crust formation using the *AFM* and $(Na + K)/Ca - A_c$ diagrams by including not only generalized rock compositions (see Fig. 1a) but also certain compositions of metamorphic and igneous rocks typical for Archean environments. Of special interest are relict rocks of the early sialic crust: "gray gneisses." The diagram in Fig. 1b shows the compositions of gray gneisses from typical provinces where these rocks are widespread (Greenland, Labrador, Scotland, etc.), and enderbiteoids of granulite complexes and tonalites and trondhjemites of granite-greenstone regions which are often compared to gray

Fig. 4. Petrochemical trends and evolutionary fields of the crust of shields. Precambrian trends: *AG* = Archean granulitic, *GT* = Precambrian granitoid, *BGT* = Eogean basite-granulitic, *BT* = basitic. Reference trends of Cenozoic volcanogenic formations: *CA* = principal calcareous-alkaline, *AB* = alkaline-basaltic, 1-4 — composition of crust and crust-forming formations of shields (1 — Anabar, 2 — Canadian, 3 — Aldan, 4 — Ukrainian): *a* — average crustal compositions, *b* — composition of principal petroformations and structural blocks, *c* — basites, *d* — granitoids. Anabar Shield (points 1-13): 1 — basite-enderbite crust, 2 — granulites of the central block [19], 3 — enderbite crust, 4 — Daldyn series [19], 5 — enderbites, SiO₂ 63-65% [24], 6 — gneisses of amphibolite facies [23], 7 — granulite crusts [13], 8 — migmatites [23], 9 — Proterozoic metamorphites [19], 10 — Khapchan series, calculated composition [22], 11 — metabasites of the Anabar complex [23, 24], 12 — granodiorites of the Lamui complex, 13 — granites of the Lamui complex [24]. Canadian Shield (points 14-23): 14 — average shield composition, 15 — Archean crust, 16 — granulite facies, 17 — amphibolite facies, 18 — Proterozoic crust, 19 — granitoids and migmatites, 20 — upper level granitoids, 21 — volcanic rocks [32], 22, 23 — average shield compositions after Pol'dervaart and Ronov [25]. Aldan Shield (points 24-46): 24 — Archean crust including granitoids, 25 — ditto, without granitoids [10,16], 26-36 — regional series and petroformations of the Aldan complex and the Aldan-Vitim massif (26 — Upper Timptonian, 27 — Iengrian, 28 — Timptonian, 29 — Jeltulin, 30 — Kabaktin, 31 — Zverev, 32 — Timptonian-Jeltulin, 33 — quartzite-condolite, 34 — micaceous marble-schists, 35 — Upper Aldan, 36 — calcareous-granulitic kuren) [10,16], 37 — acid volcanics of the bimodal series of the Olondin graben [27], 38 — metabasites, 39 — hypersthene gneisses [12, 22], 40 — low-potassium enderbites [12], 41 — enderbites [26], 42 — charnokites [13, 26], 43 — ultrametamorphic granitoids [16], 44 — leucogranites [20], 45 — late-plateau granites [12], 46 — Eogean protocrust of the Aldan-Vitim massif [10]. Ukrainian Shield (points 47-65): 47-49 — average shield composition [15, 16, 25], 50 — Archean crust [16], 51 — Lower Proterozoic [16], 52 — Archean crust [25], 53 — Proterozoic crust [25], 54, 55 — amphibolites [15, 16], 56 — charnokites [15], 57 — magmatic and ultrametamorphic complexes [16], 58 — migmatites [16], 59 — igneous rocks [16], 60 — granitoids [16], 61-65 — tectonic blocks [15, 16] (61 — Kirovograd, 62 — Golovaniev zone, 63 — Dnieper, 64 — Volyn, 65 — Podol). For *BT* trend, the composition of metabasites of the principal series of the Aldan Shield are also given (after Rudnik, Glukhovskii, and Drugova et al.): *a* — Kurul'tin, *b* — Sutam, *c* — Chogar, *d* — Upper Aldan, *e* — Fedorov, *f* — Olekmin, *k* — Kyurikan, *ol* — Olondin, *t* — Timptonian-Jeltulin.

gneisses [32, 37]. To improve the representativity of the data for metasedimentary rocks, we give the average composition of Archean argillites and sedimentary series and Lower Precambrian metagraywackes after Taylor and McLennan [36] and the mean composition of metasedimentary rocks in the East European Platform [4]. All these rocks follow a general trend in the diagram which is analogous to that of the principal rock groups (see Fig. 1a).

If we proceeded from the *AFM* diagram, we could say that, even at the earliest stages, formation of a sialic gray gneiss crust was characterized by an evolutionary trend similar to the calcareous-alkaline trend of igneous formations (from basalts to granites). We could also conclude that metasedimentary rocks and primary magmatic gray gneisses and enderbites in the middle part of the trend (between granitoids and basalts) are equivalent to andesites and other neutral magmatites. Since the rock sequence discernible on the *AFM* diagram is assumed to reflect the general petrochemical patterns of igneous evolution, a close correlation of silica and alkalis and calcium characterizing igneous differentiation should be manifested for the entire rock series (from basalts to granites). Therefore, a common calcareous-alkaline trend similar to *CA* should also be observed on the $(Na + K)/Ca - A_c$ diagram of this rock sequence.

However, from the diagram in Fig. 3 we can see that this set of igneous and metasedimentary crust-forming rocks is petrochemically nonuniform and does not follow any common evolutionary trend. This is primarily true of basalts. For these rocks, one can discern a separate trend (*BT*): from the least alkaline Archean tholeiites of greenstone belts (point 1), the TH-1 type after Condie [32] and MORB basalts (point 2), to the neutral composition of Phanerozoic basalts after Ronov et al. [25] (point 6). We can also see that schists and other sedimentary rocks are directly adjacent to granitoids

(tonalites) but not basalts. To put it differently, there are no rocks of intermediate composition (such as andesites; for comparison, the field of neutral composition of andesites of island arcs in the Pacific is marked by a triangular contour). Therefore, the set of Precambrian and other basalts, granitoids, gray gneisses, and metasedimentary rocks is clearly bimodal. This conclusion is consistent with the hypothesis of bimodal sources of the Archean continental crust [36].

Against the background of the scattered figurative points of rocks compared in the calcareous-alkaline field, a quasilinear trend (*GT*) can be seen for the true granitoids in this diagram (Fig. 3). This trend encompasses the entire consecutive series of Precambrian granitoids after Ronov et al. [25] (points 31-34), tonalites (mean composition after Condie = 0.29), and various enderbites and gray gneisses (points 16, 17, 23, 25, etc.). This cuts sharply across the main calcareous-alkaline trend of recent orogenic formations (*CA* trend). Since the rise in the importance of granitoids in the overall composition of the sialic crust can be viewed as the key indicator of the evolution of the crust, it is legitimate to ask whether this trend corresponds to the general development of the continental crust. In this context, we examined the petrochemical trends of gross crust composition during the Precambrian, with special reference to several best-explored shields.

PETROCHEMICAL TRENDS IN CRUST-BUILDING FORMATIONS AND THE EVOLUTION OF THE MEAN COMPOSITION OF THE ARCHEAN CRUST OF SHIELDS

Estimates of the average composition of the continental crust and its granite-metamorphic layer in the geochemical literature are usually based on mean data for various shields as equivalent representatives of the Precambrian crust. This evaluation overlooks the evolutionary specifics of these shields, depending on the dominance of specific crust types at certain stratigraphic levels. Yet, such differences can be considerable. The Ukrainian Shield is characterized by a large magnitude of the upper crust granitoid magmatism, while this is secondary in the Anabar Shield. In the Anabar and Aldan shields (as opposed to the Canadian and Ukrainian shields), granulites (possibly representing Early Archean protocrust) are widespread. Shields also differ in terms of the composition of metasedimentary formations and their quantitative proportions to other crystalline rocks, starting from the earliest stages of crust development. Thus, the Archean crust of the Anabar Shield consists mainly of metavolcanic granulites which contain relatively thin sedimentary rock interlayers. By contrast, the Aldan Shield and several other Early Archean (Eogean) regions of Eastern Asia exhibit well-developed sedimentary (pelitic, carbonate, etc.) rocks [10, 16].

Considering the importance of metasomatic formations in the Precambrian crust, one can assume that an objective evaluation of the evolutionary patterns should proceed not from model proportions of the main types of magmatites or metamorphites developed on shields but from the average weighted composition of the entire complex of crustal formations in large structural blocks and provinces, regional petroformations, and stratigraphic subdivisions. This approach was first taken by Eade and Fahrig [32], who conducted systematic tests of nine structural provinces on a large area of the Canadian Shield. Detailed geologic and geochemical surveys of the Precambrian crust covering large regions have been completed in the past decade. The Pacific margin of Eastern Asia was studied by Govorov and Shul'dyner (see [11]), the Aldan and Ukrainian shields by Kulish, Gorlitskii, and Yegorov [16, 17], and the Anabar Shield by Lutts, Oksman, and Rozen [19, 22-24]. As a result of these investigations, we know much more about the chemistry of the principal regional petroformations and the structural/compositional complexes of shields. The general distribution patterns of the rock-forming elements were defined for the various stages of formation of the Precambrian crust.

Much less attention was given to generalization of these data for a comparative evolutionary description of the shields. Petrochemical analysis provides a reliable basis for such a description. To this end, we combine recent data on several of the best-studied shields to observe a representative of the chemical composition for evaluation of the petrochemical trends on the $(\text{Na} + \text{K})/\text{Ca} - A_c$ diagram. The following categories of geological objects are included in the sample: 1) regional petroformations (complexes, series, etc.); 2) large tectonic blocks of shields (structural provinces and zones); 3) the mean composition of the crust of the shields for individual stages of the Precambrian; 4) the mean composition of the crust of the shields as a whole; 5) the mean composition of the principal types of metamorphites and magmatites.

The sample includes 65 chemical compositions recalculated in petrochemical parameters and plotted on a trend diagram (see Fig. 4). Proceeding from mean crust composition and several typical formations, we can contour on this diagram the evolutionary field for each shield, which display the principal petrochemical trends of the sialic crust: *AG* = Archean granulitic, and *GT* = granitoid Precambrian (the names are conventional and represent differences used in comparative descriptions of trends). Aside from these trends, the *BT* trend in the left part of the diagram (as in Fig. 3) combines the average composition of basites from the granulitic complexes of the basement and amphibolites from granite-greenstone regions. The isolated position of this trend in the diagram clearly indicates the genetic autonomy of a basites as a separate relict or "inert" rock type: mainly metabasalts inside the sialic crust.

The *BGT* trend also occupies a separate position, characterizing the earliest stages in the evolution of the Eogean (Catarean) basite-granulitic crust based on the composition of relict areas (lithoplinths) [10]. We discussed this trend in a previous study [8], so that we concentrate herein on trends *AG* and *GT*, which express the evolution of the principal part of the Archean sialic crust represented in the diagram by the evolutionary fields of the Anabar, Canadian, Aldan, and Ukrainian shields.

THE AG TREND

This trend combines the evolutionary fields of the Anabar and Canadian shields. According to geological and geophysical data [19, 22, 24], the Anabar Shield is a deeply eroded root portion of a block of the Archean crust. This explains the dominance of granulites (enderbites) and the limited presence of late potassium granites typical for the top part of the differentiated crust of other shields. The evolutionary field of the Anabar Shield along the lower segment of the trend is bounded by figurative points 4 (trend bottom) and 6 at the boundary with the field of the Canadian Shield. Point 4 represents the oldest Daldyn series, which is substantially basitic, and point 6 represents the gneisses of amphibolite facies [19]. We calculated the mean composition of the crust for this shield from the proportions of main rock types [24] with adjustment for crystal schists (point 1) and without crystal schists for the enderbitic sialic crust proper (point 3). The average composition of the most widespread granulites (point 2) and enderbitoids (point 5) after Rozen et al. and the model composition of protocrust after Dobretsov (point 7) were included as other benchmarks.

The composition of metacarbonate rocks (Khapchan series, point 10) is outside the main evolutionary field of the Anabar Shield and is complementary with respect to enderbitoids (point 5). This shows that the appearance of sedimentary rocks in the course of transformation differentiation of primary granulitic crust may have been an important factor in crust debasification conducive to higher concentrations of alkalis during metasomatic and ultrametamorphic transformations (enderbitization and charnokitization).

In contrast to the mainly Archean granulitic crust of the Anabar Shield, the Canadian Shield displays a complicated tectonic ensemble of blocks of Archean and Proterozoic crust. The Early Archean crust has survived only in relict areas [18, 31-33]. Despite the variety of structural and chemical complexes in this Shield, a systematic area survey found that the general petrochemical characteristics of the Archean and Proterozoic crusts coincided almost perfectly (points 15 and 18). The Archean and Proterozoic provinces are similar in SiO_2 and Al_2O_3 contents, and the difference in the amounts of Na_2O and K_2O does not exceed 0.6-0.8% [30]. The compositions of the rocks of granulitic and amphibolite facies also coincide almost completely (points 16 and 17).

The similarity of recurring tectonic settings in Archean and Proterozoic granite-greenstone regions can also be viewed as a factor which contributes to the stability of average compositions in the Canadian Shield [31]. Thus, the gross composition of the Archean crust, which experienced partial destruction in the course of initial formation of mobile Proterozoic belts, underwent no substantive change on the scale of major structural blocks.

THE GT TREND

This trend mainly reflects the evolution of the crust of the Ukrainian Shield, and primarily the Aldan Shield, because the latter is largely associated with the Early Archean *BGT* trend. The positions of the figurative points with respect to these trends indicate that the evolution of the composition of the Early Archean crust was controlled by basaltoid volcanic activity and subsequent exogenous transformation of volcanites followed by metamorphism and accumulation of deeply differentiated metasedimentary strata up the most selective compositions of high-alumina and high-silica formations

TABLE 1. Evolutionary Stages and Average Composition of Shields

Component	Stage				
	Early (Archean)		Late (Archean-Proterozoic)		
	Anabar Shield AG	Aldan Shield GT	Canadian Shield AG	Ukrainian Shield GT	
SiO ₂	61,2	64,9	66,6	67,0	68,7
Al ₂ O ₃	15,6	14,4	16,2	15,3	14,5
FeO, Fe ₂ O ₃ } MnO, TiO ₂ }	8,3	6,9	4,6	5,8	5,5
MgO	3,4	3,1	2,2	2,3	1,5
CaO	6,2	5,3	3,5	3,6	3,0
Na ₂ O	3,8	2,7	4,0	3,2	3,2
K ₂ O	1,5	2,7	2,9	2,8	3,6
K ₂ O/Na ₂ O	0,4	1,0	0,7	0,9	1,1

Note. Compositions (after [17, 24, 25, 32]) are evaluated by 100% without H₂O, CO₂, and P₂O₅. AG and GT are trends.

deeply differentiated metasedimentary strata up the most selective compositions of high-alumina and high-silica formations (points 33 and 35). Another direction of this evolution (the GT trend) which mainly affected the later stages of the Precambrian history of the Aldan Shield was characterized by increasing magnitude of ultrametamorphogenic and intrusive-anatectic granite formation. According to new geophysical data, alteration of deep granitoids inside major Archean blocks was almost isochemical [9]. The typical compositions for the GT trend are widespread biotite-hypersthene gneisses and enderbites (points 39 and 41) and ultrametamorphic granitoids (points 43 and 44). This trend is also followed by the average compositions of acid volcanics of Upper Archean/Lower Proterozoic age and ancient stage granitoids (points 37 and 45, after [12, 26]).

The evolutionary field of the Ukrainian Shield is contoured primarily by the figurative points of the mean crustal compositions for various stages of the Archean and Proterozoic [16, 26] and the shield as a whole: from the Archean crust (points 50 and 52) to the Lower Proterozoic (point 51) and the average compositions from the shield (points 47-49). The mean compositions of the major tectonic blocks — Kirovograd, Dnieper, and others — lie within this evolutionary field contour (points 61-65). Though the blocks are widely different in ratios and compositions of Archean and Proterozoic formations, their gross compositions by the main petrochemical parameters are similar to the mean values for the shield after Kulish and Gorlitskii (point 47). Similar to the Canadian Shield, this fact indicates close conjugation (complementarity) of the compositions of metasedimentary, ultrametamorphic, and igneous (mainly granitoid) formations with respect to initial Archean crust.

Despite their general petrologic similarity, the AG and GT trends express two different evolutionary tendencies which are reflected on the diagram in Fig. 4 by two parallel series for Precambrian crust. For each of these two evolutionary series, one can identify two consecutive stages in crust formation based on the relationship between evolutionary fields: early and late stages (this, of course, does not imply any direct synchronism of evolutionary events in different regions). Judging by the position of the evolutionary fields relative to the AG and GT trends (Fig. 4), the Anabar and Aldan shields are evolutionary analogues for the early stage, while the Canadian and Ukrainian shields are analogues for the late stage.

Crustal evolution according to the AG trend is more clearly expressed in those continental blocks where the inheritance of the chemism of primary granulitic crust is greater: higher alkalinity mainly because of higher Na₂O content, higher alumina content, and lower silica content. The GT trend represents a protracted evolutionary development which was completed by more intense granitization, resulting in higher silicity, with K₂O ≥ Na₂O (see Table 1).

In different parts (protoshields) of the ancient protocontinent, the sialic crust evolved with different intensity depending on the original evolutionary trend. Accordingly, the transition from low-alkaline granulite-basite and gray gneiss crust to normal calcareous-alkaline sialic crust was completed earlier in some shields than in others. The main condition for this transition, as indicated by the AG and GT trends cutting sharply across the main trend of recent orogenic volcanism

(CA trend) and the trend bundle of the basaltoid series as a whole, was a much higher alkalinity gradient compared to the processes of differentiation of basaltic and andesitic magmas in recent orogenic and geosynclinal regions.

* * *

Our petrochemical analysis suggests that formation of the Archean continental crust and its upper granite-gneiss envelope was controlled by peculiar petrochemical trends not compatible with the trend of massive volcanogenic formations in recent regions of continental crust growth (island arcs and active continental margins). The evolutionary direction of Precambrian sialic trends reflects the dominant role of intracrustal ultrametamorphism and granite formation processes as opposed to mantle volcanic activity. The material of recycled sedimentary rocks made an important contribution to crust formation.

Another basic difference between Precambrian crust-building formations and orogenic geosynclinal basalt-andesite-dacite series is the separation between the composition of basitic and acid rocks, i.e., the absence of a common evolutionary series. This confirms previous theories [36] of bimodal sources of Archean sedimentary formations and the crust as a whole.

To summarize, we can say that the regularities established by our analysis impose significant restrictions on the applicability of recent mobilistic concepts of the mechanisms and sources of continental crust growth to the Precambrian history of continents.

LITERATURE CITED

1. Yu. A. Balashov, A. N. Vinogradov, and F. P. Mitrofanov, "Isotopic-geochemical and petrologic data on the formation and transformation of protocrust," in: *The Early Crust: Composition and Age* [in Russian], Nauka, Moscow (1991), pp. 102-112.
2. A. A. Beus, *The Geochemistry of the Lithosphere* [in Russian], Nedra, Moscow (1981).
3. O. A. Bogatkov, L. V. Kosareva, and B. V. Sharkov, *Average Chemical Composition of Igneous Rocks* [in Russian], Nedra, Moscow (1987).
4. S. V. Bogdanova, *The Earth's Crust of the Russian Plate during the Early Precambrian* [in Russian], Nauka, Moscow (1986).
5. L. S. Borodin, *The Petrochemistry of Igneous Series* [in Russian], Nauka, Moscow (1987).
6. L. S. Borodin, "Petrochemical trends and classification of gabbro-granitoid series," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 11, 3-13 (1988).
7. L. S. Borodin, "Petrochemical trends and the origin of Early Archean gneiss-amphibolite series of the Middle Dnieper region," in: *The Early Crust: Composition and Age* [in Russian], Nauka, Moscow (1991), pp. 151-157.
8. L. S. Borodin and B. N. Altukhov, "Petrochemistry of the ancient granitoids of the southern Siberian Platform and its folded surroundings," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 11, 39-51 (1991).
9. A. N. Vinogradov and G. V. Vinogradova, "Geochemical types of primary crustal granites," in: *The Oldest Granitoids of the USSR* [in Russian], Nauka, Moscow (1981), pp. 49-57.
10. *A Geochemical Model of the Pacific Margin of Asia* [in Russian], Nauka, Moscow (1984).
11. M. S. Markov (ed.), *The Deep Structure of the Territory of the USSR* [in Russian], Nauka, Moscow (1991).
12. M. Z. Glukhovskii, *Geologic Evolution of the Basement of Ancient Platforms* [in Russian], Nauka, Moscow (1990).
13. N. L. Dobretsov, *Introduction to Global Petrology* [in Russian], Novosibirsk, Moscow (1980).
14. V. A. Rudnika (ed.), *The Oldest Rocks of the Aldan-Stanovoy Shield: A Guide to International Geologic Excursion No. 280* [in Russian], VSEGEI, Leningrad (1989).
15. Yu. P. Yegorov, "The chemical composition of rocks, regional clarkes, and the geochemical background of the chemical elements of the Ukrainian Shield," *Geol. Zh.*, **45**, No. 2, 83-95 (1985).
16. B. A. Kulish and B. A. Gorlitskii, *Petrochemistry of Precambrian Complexes of the Ukrainian and Aldan Shields* [in Russian], Naukova Dumka, Kiev (1989).

17. A. A. Kremetskii and L. N. Ovchinnikov, *The Geochemistry of Deep Rocks* [in Russian], Nauka, Moscow (1986).
18. B. G. Lutts, *Magmatism of the Mobile Belts of the Early Earth* [in Russian], Nauka, Moscow (1985).
19. B. G. Lutts and V. S. Oksman, *Deeply Eroded Fault Zones in the Anabar Shield* [in Russian], Nauka, Moscow (1990).
20. Z. I. Petrova, *The Geochemistry of Granulite-Gneiss Complexes of the Precambrian* [in Russian], Dissertation for the degree of doctor of geological-mineralogical sciences, Institute of Geochemistry, Siberian Department, USSR Academy of Sciences, Novosibirsk (1989).
21. B. Windley (ed.), *The Early History of the Earth* [Russian translation], Mir, Moscow (1980).
22. O. M. Rozen, V. P. Andreev, A. N. Belov, et al., *The Archean of the Anabar Shield and the Early Evolution of the Earth* [in Russian], Nauka, Moscow (1988).
23. O. M. Rozen, "Two types of earth's crust in the Anabar Shield," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 6, 3-16 (1990).
24. O. M. Rozen, "Formation of the Earth's crust of the Anabar Shield," Dissertation for the Degree of Doctor of Geological-Mineralogical Sciences, Institute of the Lithosphere, Russian Academy of Science, Moscow (1992).
25. A. B. Ronov, A. A. Yaroshevskii, and A. A. Migdisov, *The Chemical Structure of the Earth's Crust and the Geochemical Balance of Its Principal Elements* [in Russian], Nauka, Moscow (1990).
26. V. A. Rudnik and E. V. Sobotovich, *The Early History of the Earth* [in Russian], Nauka, Moscow (1984).
27. A. V. Sochaeva, *Petrochemistry of the Upper Archean and Proterozoic of the Western Aldan-Vitim Shield* [in Russian], Nauka, Leningrad (1986).
28. V. N. Kholodov, "The evolution of the composition of supply provinces in the history of the earth," in: *Problems of the Lithology and Geochemistry of Sedimentary Rocks and Ores* [in Russian], Nauka, Moscow (1975), pp. 191-209.
29. V. N. Kholodov, "The relationship between sedimentation and magmatism in the Precambrian," *Litol. Polezn. Iskop.*, No. 3, 3-26 (1989).
30. K. Condie, *Archean Greenstone Belts*, Elsevier, Amsterdam (1981).
31. K. Condie, *Plate Tectonics and Crustal Evolution*, 3rd ed., Pergamon, London (1989).
32. K. E. Eade and W. T. Fahrig, "Geochemical evolutionary trends of continental plates: A preliminary study of the Canadian Shield," *Bull. Geol. Surv. Canada*, No. 179 (1971).
33. P. F. Hoffman, "Precambrian cratons of North America," *Proc. 28th IGC (abstr.)*, Vol. 2, pp. 64-65 (1989).
34. R. W. Le Maitre, "Chemical variability of some common igneous rocks," *J. Petrol.*, 17, No. 4, 589-598 (1976).
35. L. T. Silver and B. W. Chappell, "The peninsular range batholiths of southwestern North America," *Earth Sci.*, 79, 105-121 (1988).
36. S. R. Taylor and S. M. McLennan, *The Continental Crust: Its Composition and Evolution*, Blackwell, London (1985).
37. F. Barker (ed.), *Trondjhemites, Dacites, and Related Rocks*, Elsevier, Amsterdam (1979).

PROBLEMS OF ISOTOPES AND SULFATE REDUCTION IN SEDIMENTARY – VOLCANOGENIC COMPLEXES OF THE KUKASOZERO ZONE

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In the article, we discuss the results of an isotopic analysis of the sulfur in the background mineralization of highly carbonaceous rocks. Conclusions are drawn concerning the diagenetic origin of the sulfides and the role of sulfate reduction. We discuss the somewhat anomalous character of the sulfides of the Kukasozero zone with reference to the distribution pattern of isotopically characterized sulfides of the Baltic shield.

The geochemical cycle of sulfur is governed by the circulation in the land–ocean system and by movements of sulfur back and forth from the sulfide-sulfate state to dissolved and gaseous states. Changes in valence state during reducing reactions and certain equilibrium exchange reactions are accompanied by various degrees of isotope fractionation. The most powerful natural process of isotopic separation is bacterial sulfate reduction. The reduction of sulfate ions is carried out by anaerobic bacteria, which are abundant in almost all saline and fresh-water basins. As early as the 1950s, laboratory experiments with suspended bacteria demonstrated that the H_2S formed is enriched with ^{32}S by $\approx 25\%$ over the original sulfate [8]. Under conditions actually occurring in nature, however, bacterial reduction can result in a 40–45% enrichment of sulfides with the light isotope [41]. This can probably be explained by differences in the action of bacteria under laboratory and natural conditions. The enormous amount of data on the isotope characteristics of sulfur in recent marine, oceanic, and lacustrine sediments, obtained in the 1950s–1980s as a result of vigorous progress in marine geology (in particular, the deep-sea drilling project), showed that under conditions where supplementary sources of sulfur are absent, metabolic hydrogen sulfide and sulfide compounds almost always have very light isotope markers. Substantial differences in isotopic composition can be explained by many factors: different rates of sulfate reduction at each individual-sampled site, closure of an isotopic-geochemical system (in an actual lithological-geochemical setting), etc.

Maximum sulfate reduction is found in sediments rich in organic matter. In such sediments, the content of sulfide minerals is substantially elevated because of stagnant conditions.

A widespread distribution of background sulfides with light isotope compositions has been found in sedimentary strata of all age intervals, including the Precambrian [12]. The finding of sulfate reduction in the Early Precambrian is very important, since it indicates widespread distribution of bacteria, in particular, bacteria in biogenic associations, understood in the broadest sense, and also tells us something about the stages in the evolution of the atmosphere and the actual atmospheric content of oxygen.

These conclusions were recently arrived at [12, 15]; the only question still being discussed is the possibility that biogenic sulfate reduction may have occurred during the Early Archean under conditions when basins were located on primitive continental crust.

During isotopic-geochemical investigations of sulfur in presumably sedimentary sulfates and sulfides of the Blind-River (Ontario) [13], Barberton (Southern Africa), and Pilbara (Western Australia), a number of authors found almost identical isotopic compositions similar to the meteoric composition ($\pm 4\%$). On the basis of the results obtained, it was concluded that no sulfate reduction occurred during the Early Archean stages. At the same time, data on Early Archean sulfates and sulfides of the Southwestern Pamirs and Aldan [2] suggest that sulfate reduction was already taking place during the Archean.

As mentioned above, the Early Proterozoic was an epoch with well established sulfate reduction, an atmosphere in which oxygen was present in quantities equally no less than 5–10% of its present-day amount [15], and favourable and

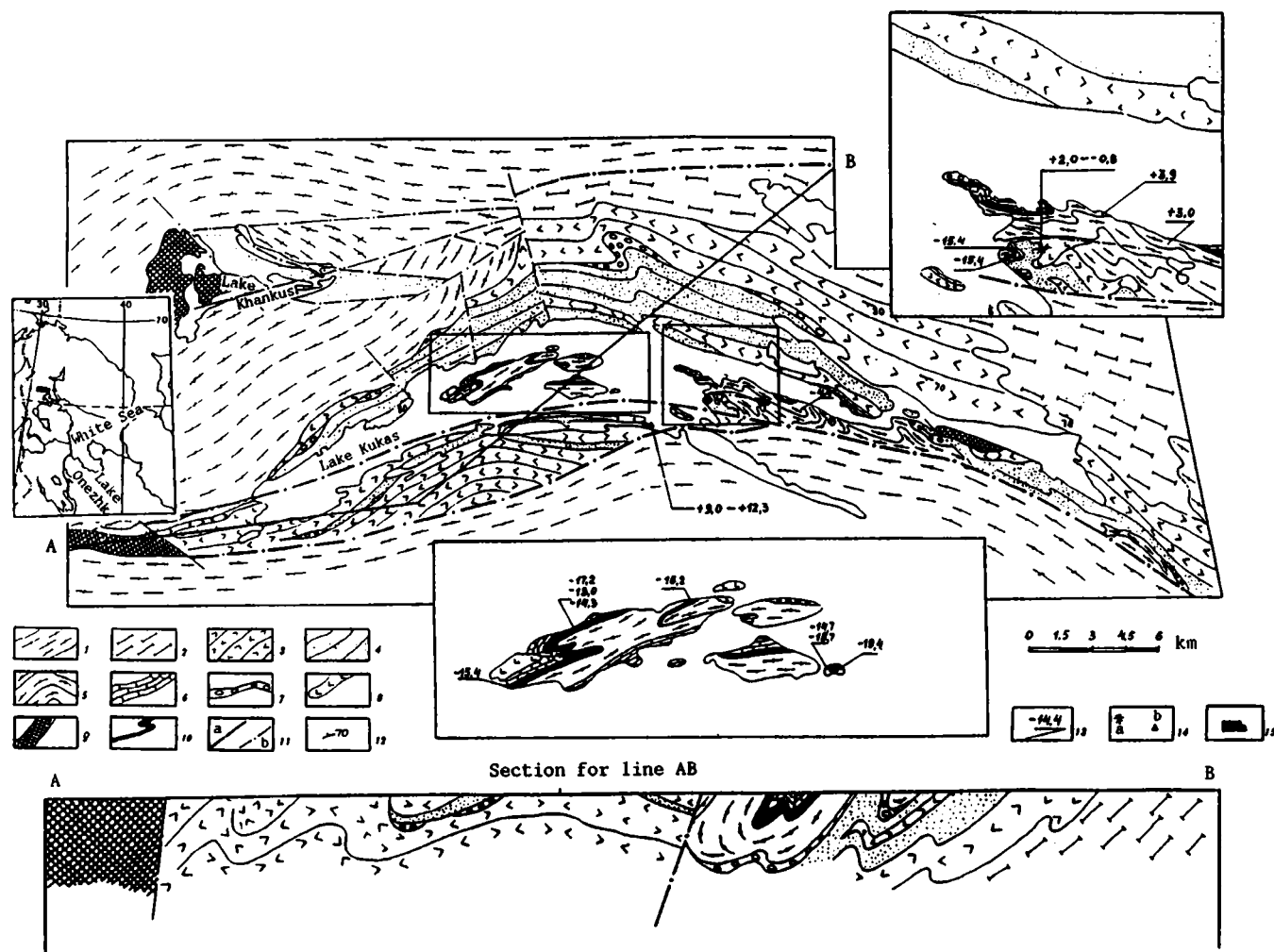


Fig. 1. Schematic geological map of the Kuksozero sinclinorium with isotopic-geochemical characterization of the sulfide mineralization. 1) Lower Archean gneiss, granite, and migmatite; 2) Upper Archean Lopiysk rock complex (crystalline schists); 3) Lower Proterozoic Kuksozero amphibolite, plagioclase amphibolite; 4) micaceous-quartz-feldspar schist; 5) Lower Proterozoic Khirvinavolok member with interstratification of garnet-amphibolite, staurolite- and kyanite-bearing garnet-mica-amphibolite and amphibolite-carbonate schist; 6) Lower Proterozoic Khirvinavolok carbonate rocks; 7) Lower Proterozoic Khirvinavolok conglomerate; 8) high-magnesian magmatites; 9) ultramafic rocks; 10) Lower Proterozoic Khirvinavolok conglomerate; 11) deeper (a) and shallower (b) fissures; 12) attitudes; 13) $\delta^{34}\text{S}$ of sulfides; 14) ore shows (a: Khirvinavolok, b: Kolchedannoye); 15) study area.

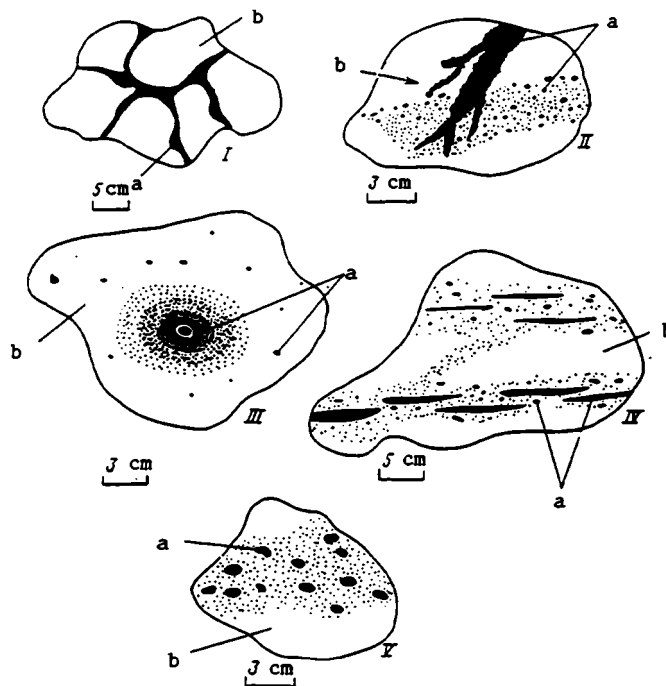


Fig. 2. Textural varieties of sulfide mineralization: I) veinlet; II) veinlet-disseminated; III) concretionary-disseminated; IV) layered-lenticular-disseminated; V) irregular-disseminated, streaky-disseminated; a) ore minerals (primarily pyrite-pyrrhotite); b) highly carbonaceous schists.

quite aerially heterogeneous biogenic life activity, as evidenced by the accumulation of a enormous amount of carbonaceous material over a period of ≈ 2 billion years.

These far-reaching conclusions have been made on the basis of a fairly limited amount of data on objects which do not constitute a very representative sample, since the objects studied are large, very well known deposits, key "geological sites," etc., and, occasionally, background sulfide mineralization in "typical" metasedimentary strata. Therefore, the accumulation of data on background mineralization can, on the one hand, to large extent, reveal the specific nature of the sedimentogenesis and diagenesis in ancient basins of the specific region and, on the other hand, in certain respects correct our fundamental concepts concerning these phenomena.

In this report, we will discuss results concerning the sulfur isotopy of sulfides in carbonaceous strata in the eastern part of the Baltic shield. With reference to the overall distribution pattern of $\delta^{34}\text{S}$ in the background sulfide mineralization of the Baltic shield, we characterized the isotopic composition of the sulfur in the Kukasozero synclinorium, which is associated with a certain anomaly in the sulfur isotopy of sulfides.

Geological Setting and Geochemical Characterization of the Object. The Kukasozero synclinorium, a part of the Northern Karelian zone, is located in the center of the Baltic shield and extends in a sublatitudinal direction for 50-70 km (Fig. 1).

The synclinorium is a narrow, elongate zone "pressed" between the Belomorsk and Karel'sk complexes. To the east, as if continuing the Lower Proterozoic structure, one finds Upper Archean formations which are part of the Tiksheozero structure.

A two-part stratigraphic classification of Lower Proterozoic formations is the most popular [3]. The Kukasozero suite, correlating with the Jatulian system, and the overlying Khirvinavolok suite (the Lyudikoviy system), differ substantially with respect to lithological-petrographic composition.

TABLE 1. Isotopic Composition of Sulfur in Sulfides of Lower Proterozoic Sedimentary and Volcanogenic-Sedimentary Formations of the Kukasozero Synclinorium

Sample No.	Collection site	Description of host rock	Mineral type of sulfide	Textural-structural characterization of sulfide mineralization	$\delta^{34}\text{S}$, ‰
Khirvinavolok Ore Show (Kukasozero suite)					
GR-35/1	Khirvinavolok Peninsula	Essentially quartz metasandstone	Chalcopyrite, bornite; chalcopyrite clearly predominates	Densely disseminated	+1.7
GR-35/2	Same	Micaceous, essentially quartz metaconglomerate	Same	Same	+0.5
GR-35-3	"	Same	Chalcopyrite	Veinlet-disseminated	+2.0
GR-35/4	"	Contact of high-magnesium base rock and metasandstone, intersecting quartz vein (ore channel)?	Pyrite	Coarse streaky segregation	-0.8
GR-35/5	"	Micaceous metaquartzite near contact (see GR-35/4)	Chalcopyrite	Concordant lenticular-disseminated	-0.1
GR-38	"	Metaquartzite	"	Disseminated	+1.8
GR-38/1	"	"	"	"	+2.0
GR-38/2	"	"	Pyrite	Lenticular-disseminated	+0.1
Kolchedannoe Ore Show (Kukasozero suite)					
GR-40	Small island at the south-east tip of Kukas Island	Calcite-tremolite schist	Pyrite (bulk)	Disseminated coarsely crystalline	+12.3
GR-40k	Same	Same	Cubic pyrite (from Sample GR-40)	Same	+9.6
GR-40p	"	"	Pyrite, pentagonododecahedral (from Sample GR-40)	"	+10.4
GR-100	"	Predominantly tremolite schist	Pyrite	"	+10.8
GR-100/1	"	Rosy coarse-crystalline carbonate (calcite)	"	Megacrystalline disseminated	+12.6
GR-100/2	"	Quartz vein	"	Disseminated	+9.2
GR-100/3	"	Quartz-tremolite schist	"	"	+9.0
Interbedded stratum of amphiboles, amphibole-garnet-micaceous, quartz-amphibole-carbonate schists (flyschoid and Khirvinavolok beds)					
GR-7/20	Northeastern part of the Khirvinavolok Peninsula	Amphibolite	Pyrrhotite	Disseminated mineralization	-0.1
GR-119/2	Same	Carbonatized amphibole-quartz-biotite schist	"	Same	-4.4

TABLE 1 (continued)

Sample No.	Collection site	Description of host rock	Mineral type of sulfide	Textural-structural characterization of sulfide mineralization	$\delta^{34}\text{S}$, ‰
GR-115	"	Amphibolite	Pyrite	Dissemination and small schlieren	+3.9
GR-115a	"	"	"	Same	+3.0
Stratum of Highly Carbonaceous Rock (Khirvinavolok Suite)					
GR-215/1	Northern part of Petrov Island	Highly carbonaceous rock	Pyrite	Lenticular-veinlet	-17.2
GR-215/2	Same	With maximum (40%) content of carbon	Pyrite, pyrrhotite	Microconcretions	-13.0
GR-7/16	"	Highly carbonaceous rock	Pyrrhotite, chalcopyrite	Flat 4-cm, zoned concretion	-14.3
GR-214	Western part of Petrov Island	Same	Pyrite	Disseminated, pockety	-15.4
GR-217	Small island along the eastern extension of Monastyrskiy Island	"	Pyrrhotite	Thin-lenticular	-19.4
GR-219	400 m east of GR-217 site	Carbonaceous-amphibolite schist	Pyrite	Lenticular-veinlet	-14.7
GR-219/1	Same	Rock analogous to GR-219, but with large content of carbon		Disseminated-veinlet	-18.7
GR-220	Khirvinavolok Peninsula, in the vicinity of the Cu-ore show	Carbonaceous-amphibole-garnet schist	Pyrite, pyrrhotite	Layered-veinlet	-15.4
GR-220/1	Same	Amphibole-carbonaceous schist	Pyrite	Layered-veinlet, pockety	-15.4

The section of the Kukasozero suite consists of three members: 1) conglomerate; 2) amphibolites and plagioclase-amphibolites; 3) feldspar-quartz, quartz-feldspar, micaceous-quartz-feldspar, and essentially micaceous schists [10]. Reconstruction of the original composition of the rock [7] transforms the section, which then consists of: 1) conglomerates; 2) volcanites of basic composition; 3) feldspathic-quartzitic sandstones and silty sandstones. The thickness of the suite varies from hundreds of meters to 2 km.

The reference section of the Khirvinavolok suite with reconstructed [7] premetamorphic analogs takes on the following appearance: 1) conglomerates containing a gravel of Archean gneisses, puddingstone of uncertain origin; 2) massive carbonate rocks with traces of mottling; 3) an interbedded member of garnet-amphibole, staurolite- and kyanite-bearing garnet-mica-amphibole schists and carbonate, amphibole-carbonate rocks (an interbedded member of fine-grained rock in the sandy and pelitic range), clastic and carbonate rocks (an interbedded member of fine-grained, flyschoid-type clastic and carbonate rocks with sandy and pelitic grain sizes); 4) banded amphibolites (carbonate-sandy clays); 5) graphitic shales (carbonate-clayey-carbonaceous aleurolites); 6) an interbedded, essentially carbonate stratum consisting of interlayers

of carbonate (70-80%) predominantly of the calcite type and quartz-sericite-feldspar schist (20-30%). The rocks of the Kukasozero and Khirvinavolok suites are metamorphosed to the rank of low- and intermediate-temperature amphibolite facies [5].

In structural plan, the deposits of the Kukasozero suite in-fill the border of the Kukasozero synclină and occur along the southern and northern shores of lake Kukas. The deposits of the Khirvinavolok suite occur in the center of the synclinorium. The rocks composing the Khirvinavolok suite are substantially more diverse in grain size, ranging from fine pelitic varieties to very coarse-grained varieties (conglomerates). In general, however, the material is substantially finer, with elevated contents of carbon and aluminum and individual packets which are flyschoid in character. From the point of view of facial relations, the deposits of this suite are deeper [10].

The black shale rocks occurring on the islands of the lake and on the Khirvinavolok Peninsula are characterized by elevated sulfide content. The content of carbon in the rock varies from 5 to 40%. Sulfide-carbonaceous schists contain elevated quantities of Cu, V, Ni, Cr, Zn, and Co [10]. The content of ore minerals in the rock varies from 1 to 30% and averages ~8%. Pyrrhotite and pyrite predominate, with subordinate quantities of chalcopyrite, sphalerite, ilmenite, and rutile; hematite, pentlandite, cubanite, bornite, molybdenite (?), and cobaltite (?) are occasionally present.

Pyrrhotite, like pyrite, is present in the form of two generations differing in morphology, grain size, and degree to which it is idiomorphic.

Disseminations are the most abundant mode of occurrence of sulfides. There are equigranular-disseminated, mottled, indistinctly-layered- disseminated varieties (Fig. 2). In addition, there are numerous veins and variously oriented splits predominantly filled with pyrrhotite. Occasionally, one can find streaky and concretionary formations.

In general, the ore mineralization is sedimentogenic-diagenetic in character, with subsequent recrystallization and transformation during the stage of metamorphism, up to the point of the emergence of metamorphogenic-veinlet varieties.

RESULTS OF ISOTOPIC ANALYSIS AND DISCUSSION OF DATA OBTAINED

The isotopic analysis was carried out in the Laboratory of Geochemistry and Geochronology of the Institute of Geological Sciences, the Russian Academy of Sciences. Rocks containing sulfides were crushed and sieved to grain sizes providing a pure sampling of the minerals to be analyzed. Monofractions were sampled with the aid of a binocular microscope. The sulfides were converted to SO_2 according to a standard methodology. The gas obtained was analyzed on a MI-1201B mass spectrometer. Values of $\delta^{34}\text{S}$ are given in permills relative to the "Shikote-Alin" meteorite standard. The reproducibility of $\delta^{34}\text{S}$ was 0.5%.

The data obtained are characterized by sharply negative values of $\delta^{34}\text{S}$ (see Table 1 and Fig. 3) and relatively small scatter (-13.0 to -19.0%).

We did not find substantial differences between the isotopic compositions of sulfur in pyrite, pyrrhotite, and chalcopyrite of different generations. The distribution of isotopically characterized sulfides with respect to textural-structural features did not take the appearance of a clearly expressed function. One can only suppose that the sulfides in concretionary forms are of a somewhat heavier isotopic composition than the sulfides in other forms.

The isotopic composition of sulfur in the sulfides was investigated in samples from various parts of the section of carbonaceous rock and from various points along a line: the Petrov Islands, Monastyrskiy, a number of small unnamed islands, and the Khirvinavolok Peninsula (see Fig. 1). We did not find clearly expressed patterns in the distribution of the isotopically characterized sulfides.

The sharply negative values of $\delta^{34}\text{S}$ in sulfides disseminated in carbonaceous rock suggests that these sulfides were formed during diagenesis in a process of biogenic sulfate reduction.

The relatively small scatter in the data, which is uncharacteristic of diagenetic sulfides, can be explained by averaging during metamorphic recrystallization and remobilization of ore matter into individual, thin metamorphogenic veinlets. Though there is little doubt that the disseminated sulfides are diagenetic in origin, this fact substantially complicates efforts to infer the isotopic composition of the original sulfate which underwent reduction to form the sulfides.

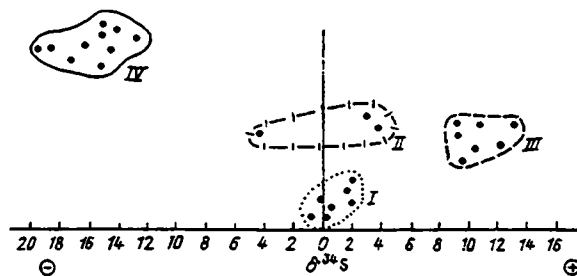


Fig. 3. Isotopic composition of sulfur in sulfides of pyritic ore shows and background mineralization of Lower Proterozoic formations of the Kukasozero zone. I) Khirvinavolok ore show; II) sulfides of the flyschoid stratum; III) Kolchedannoye ore show; IV) sulfides of highly carbonaceous rock.

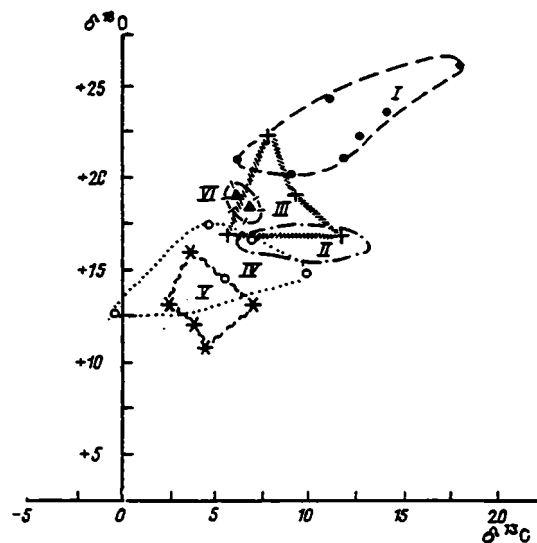


Fig. 4. Isotopic compositions of carbon and oxygen of mottled carbonate rocks of the Jatulian (Tulomozero) level of the Baltic shield. I) Onezhsk structure [11]; II) Shombozero synclinorium; III) Kuolayarvi structure; IV) Kukasozero synclinorium; V) Imandra-Varzuga zone (according to the data of B. G. Pokrovskiy and V. A. Melezhik); VI) Pechenga structure (according to the data of B. G. Pokrovskiy and V. A. Melezhik).

It is reasonable to suppose that the source of the sulfur in the sulfides was sulfate from the sea water of the Lower Proterozoic paleobasin. In this case, the isotopic composition of the sulfur in the marine sulfate would substantially depend upon the character, size, and degree of openness of the paleobasin. Here, there are two variants of sulfate formation: 1) the paleobasin in the Northern Karelian zone occupied a relatively narrow, isolated area, therefore, the isotopic composition of the sulfur in the sulfate probably differed substantially from the "oceanic constant," which, according to a number of authors [2], was close to the present-day value during Lower Proterozoic times; 2) the paleobasin was a broad water expanse, including regions where we now find deposits of the Imandra-Varzuga, Northern Karelian, and other complexes; in this variant, the isotopic composition would correspond to the "oceanic constant." The available data do not give reason to favor one hypothesis over the other.

Moreover, inflow of sulfate-bearing brines of various origins into the bottom waters and muddy waters of the paleobasin may well have taken place. The fact of the matter is that in all the Lower Proterozoic structures of the Baltic shield, Ludikovian formations with a complex of carbonaceous rocks are underlain by Jatulian mottled, clastic-carbonate

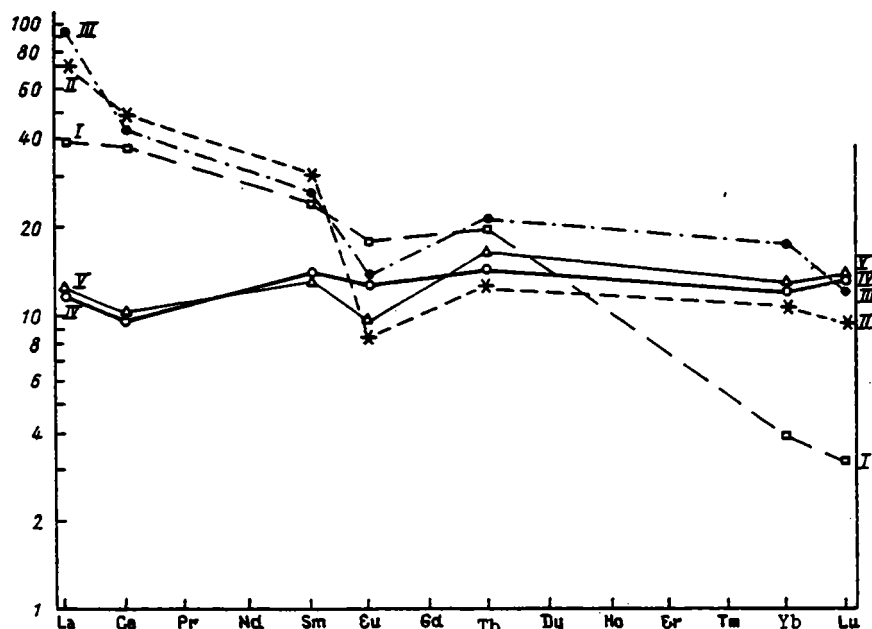


Fig. 5. Chondrite-normalized distribution of REEs of Lower Proterozoic volcanogenic-sedimentary rocks of the Kukasozero synclinorium. I) hydrothermally altered metasediments near Khirvinavolok ore show; II) metasediments further from the Khirvinavolok ore show; III) highly carbonaceous rocks of Petrov Island; IV) high-magnesian basic magmatites near the Khirvinavolok ore show; V) highly carbonaceous rocks of Khirvinavolok Peninsula, in relative proximity to the Khirvinavolok ore show.

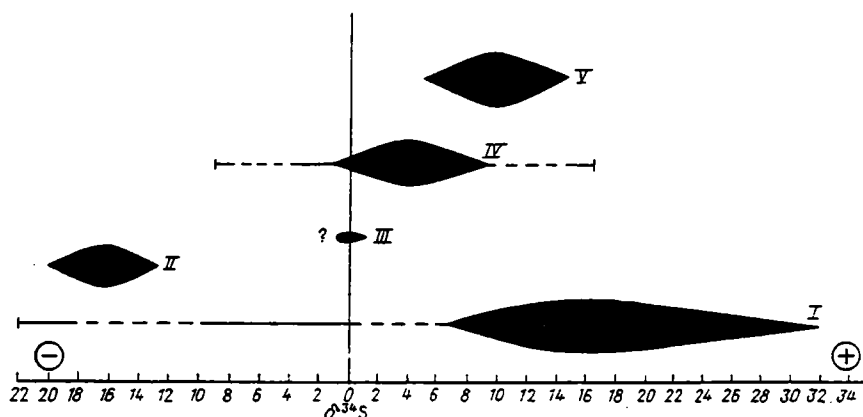


Fig. 6. Distribution of $\delta^{34}\text{S}$ for disseminated (background) sulfide mineralization of Lower Proterozoic carbonaceous rocks in the eastern part of the Baltic shield. I) shungites of the Zaonezhsk suite; II) highly carbonaceous rocks of the Khirvinavolok suite; III) highly carbonaceous rocks of the Sovayarvi suite; IV) carbonaceous phyllites of the Pil'guyarvi suite; V) highly carbonaceous rocks of the Tominga suite.

strata. The investigations by a number of lithologists and geochemists [1, 4, 6] and the data presented in this report indicate that sulfates of evaporitic origin are widely occurring in the deposits at this level. The degree to which evaporation was a factor varied markedly in different regions; this will be discussed in more detail below.

The mottled Jatulian proto-evaporitic deposits have an unusual isotopic composition of carbon (Fig. 4). This composition is characterized by a marked weighting with respect to $\delta^{13}\text{C}$ (up to $+18\text{‰}$) [11]. The mottled carbonates of the Kukasozero synclinorium are not an exception. They occur on the northeastern and southwestern shores of Lake Kukas, on small islands in the southern part of the lake, and at a number of other localities. They consist of calcite and dolomite, with the former predominating. The isotopic composition of carbon in these carbonates varied from -0.4 to

+10.0‰ (see Fig. 4), and $d^{18}\text{O}$ varies from +12.6 to +21.4‰. The isotopic composition of the oxygen reflects the isotopic equilibria at the catagenetic-metamorphic stages in the transformation of the carbonates.

The weighted composition of sulfur, which is characteristic of epigenetic sulfides associated with sulfate-bearing brines, includes pyrites of the Kolchedannoye ore show (see Fig. 3). The values of $\delta^{34}\text{S}$ in pyrites are within the range of 9.0-12.6‰ [10]. The ore show is localized in a carbonate-tremolite stratum.

Another possible source of sulfur was hydrothermal springs, which may have discharged onto the floor of the paleobasin. These discharges would have consisted of abyssal fluids, along with ultrabasic high-magnesian magmatism. The isotopic composition of sulfur in the Khirvinavolok ore show was investigated previously. Copper-pyrite metallization is localized in quartz-mica-feldspar schists (metamorphically and, probably, metasomatically altered, essentially quartz-subarkose metasandstones) of the Kukasozero suite. The banded-disseminated mineralization and thin lenses are arranged in an echelon-like pattern near a contact with basic and ultrabasic high-magnesian magmatites (see Fig. 1). The range of variations in $\delta^{34}\text{S}$ for sulfur in chalcopyrite, bornite, and pyrite is from -0.8 to +2.0‰. In essence, the sulfur in the sulfides of the ore show yields values of zero, which may indicate abyssal conditions.

An analysis of the distribution of rare-earth elements in high-magnesian basic and ultrabasic magmatites indicates a substantial difference between REE plots and plots of simple lithological-petrographic varieties in this zone (Fig. 5). Relatively low contents of light REEs and relative high contents of heavy REEs, lack of a Eu minimum, and a flattened normalization curve of samples relative to chondrite are characteristic of high-magnesian magmatites. These data, in combination with the isotropy of sulfur, support the conclusion that the magmatites are of fairly deep origin.

High-temperature sulfate-bearing hydrothermal waters containing sulfur with a zero isotopic composition may have substantially influenced the isotopic composition of the sulfur in bottom waters, though most probably over a very limited area. This hypothesis finds support in the distribution of sulfur isotopes in the sulfides of the flyschoid stratum. The material analyzed was collected in the northeastern part of Khirvinavolok Peninsula from amphibolites of an interbedded stratum. The values of $\delta^{34}\text{S}$ for pyrite were -4.4 to +3.9; sulfides were generally represented by disseminated mineralization. The sampling sites were 1-3 km from the ore show.

Thus, the isotopic composition of sulfur in the background sulfide mineralization is a result of biogenic sulfate reduction of marine sulfate. The isotopic composition of the latter is very hypothetical. It may have been influenced by local factors in the region, such as inflow of thermal brines of both abyssal and shallow origin into natural muddy waters.

Sharply negative values of $\delta^{34}\text{S}$ in disseminated sulfides resulting from sulfate reduction are very typical of stages in diagenesis. Such values are quite widespread in Proterozoic carbonaceous schists and even more widespread in recent muds, but proved to be anomalous for carbonaceous schists at the Ludikovian level of the Lower Proterozoic.

We analyzed the isotopic composition of sulfur (Fig. 6) in disseminated sulfide mineralization in carbonaceous formations of the largest Karelian structures of the Baltic shield: the Onezhsk basin, and the Kukasozero, Kuolayarvi, Pechenga, and Imandra-Varzuga zones. All of the data are original. The isotopic analysis was also carried out in the Laboratory of Isotope Geochemistry and Geochronology (Institute of Geology, Russian Academy of Sciences). The maximum range of $\delta^{34}\text{S}$ is characteristic of the pyrites of the shungitic rocks of Zaonezh'e (from -22.1 to +31.3 ‰, but if a single negative value is excluded, the range narrows to +6.0 to +31.3‰. More than half of the values lie within the region of +15.0 to +22.0 ‰ [9]. The maximum range, also the extremal values, both positive and negative, belong to the concretionary (or, more broadly, streaky-concretionary) morphological species of pyrite.

The sulfides of the Imandra-Varzuga black shale formations are the most similar sulfides in terms of isotopic composition of sulfur, but, in contrast to the shungites, are characterized by a substantially narrower range of values: +4.9 to +14.2 (see Fig. 6). These sulfides, essentially pyrite of disseminated, layered-disseminated, and lenticular structure, are localized in the carbonaceous schists of the Tominga suite, which show a substantial range of carbon contents. The collection sites of the sulfide-carbonaceous samples are located in the western part of the Imandra-Varzuga structure (Anof-II, Lysaya Mt., 45th Kilometer, etc.). Together with the disseminated ore mineralization, more concentrated sulfide accumulations are localized in the metasedimentary formations of the Tominga suite; these include the "Pyrrhotite Gorge," the Bezymyannoye in the vicinity of Anof-II, etc.

Slightly carbonaceous schists serve as the host rocks for densely disseminated, massive pyrrhotite ores of the Pyrrhotite Gorge" deposit. The deposit is situated in direct proximity, almost in contact with, the Khibinu alkalic pluton. The isotopic composition of the sulfur in the pyrrhotite is characterized by near-zero (-2.4 to 0‰) values.

The densely disseminated pyrrhotite ores of the Bezmyannoye ore show in the vicinity of Anof-II are localized in mottled hematite metaarkoses with more negative values of $\delta^{34}\text{S}$; this composition differs substantially from both that of the "Pyrrhotite Gorge" deposit and that of the background sulfide mineralization in the carbonaceous rocks.

The isotopic composition of the sulfides in carbonaceous and slightly carbonaceous flyschoids in the Pil'guyarvi suite of the Pechenga synclinal structure is very unusual. Values of $\delta^{34}\text{S}$ range from +10.8 to -8.6‰. The majority of values (19 out of 31) lie within the region of +3.8 to -2.5‰. Positive values predominate (21 out of 31). Despite the fact that the range of $\delta^{34}\text{S}$ in the background mineralization is somewhat broader than the range for sulfides in the copper-nickel ores previously studied [10], a correlation was found between $\delta^{34}\text{S}$ of the ores and the $\delta^{34}\text{S}$ of the background mineralization.

The carbonate and clastic rocks underlying the Luchlompol'sk suite show a sharply weighted (to +31.0‰) isotopic composition of sulfur in sulfides.

In Fig. 6, the $\delta^{34}\text{S}$ values for sulfides of the black shale rocks of Kuolayarvi lie within a very narrow zone near the zero mark. But, in this case, we have at our disposal only isolated values (two determinations) which are not sufficient to draw conclusions from.

Having evaluated the overall distribution of sulfur isotopes in sulfides of black shale rocks at the Lower Karelian level in almost all Lower Proterozoic structures in the eastern part of the Baltic shield, we can state that there is a predominance of heavy sulfides, sulfides of the Zaonezhsk shungites, of the carbonaceous rocks of Imandra-Varzuga, and of the Pechenga phyllites. The distance between the most extreme study objects characterized by positive $\delta^{34}\text{S}$ anomalies (in the central parts of the Onezhsk and Pechenga structures) equals ~1000 km, which suggests that the processes creating this type of isotopic composition of sulfur were regional in character.

In earlier publications [9], various hypotheses attempting to explain a positive $\delta^{34}\text{S}$ anomaly of a concrete case were discussed. The most plausible (based upon new data) hypothesis involves the possible participation of thermal sulfate-bearing brines in the formation of diagenetic sulfide mineralization in carbonaceous sediments. This hypothesis is supported by a compilation of data on the Jatulian level of evaporite deposits [1]. Finds of sulfates, predominantly barite, in the form of small, dispersed segregations of predominantly sedimentary-diagenetic origin, numerous pseudomorphs after gypsum, the mottled coloration of the clastic-carbonate complex in which stromatolitic bioherms are widely distributed, the presence of specific geochemical and isotopic-geochemical anomalies, and several other facts confirm the reality of such a level. It is now possible to trace this level in all of the Lower Proterozoic structures and to demonstrate its regional character. In addition, only the lack of reliable correlation criteria (especially geochemical criteria) prevents the "tracing" of this level in sections of other shields. The characteristics of the arid sedimentation in the various Proterozoic paleobasins reflect the scales of sulfate accumulation in each individual paleostructure. In turn, the scale of sulfate accumulation had a substantial influence on the volumes of brine formed during subsequent stages in the transformation of the rock and on the possible action of this secondary brine upon the Ludikovian formations. Proceeding from these premises, it is easy to explain the patterns we discovered: the maximum of sulfate accumulation during the Jatulian in the Onezhsk basin, the Imandra-Varzuga zone, the correspondingly maximally weighted composition of the sulfur in the "background sulfides" of the Ludikovian, the proposed minimum of sulfate accumulation for the paleobasin in the Kukasozero zone, and the absence of influences of brines on the background mineralization (only the isotopic composition of pyrite in the Kolchedannoye ore show, localized in Jatulian formations indicates possible participation of sulfate brines). The source of the sulfur for the sulfides in the carbonaceous rocks of the Ludikovian level of the Pechenga structure was probably a multiple in nature (weighted because of some amount of brine sulfate and some amount of abyssal sulfate); this is reflected in the isotopic composition of the sulfur.

* * *

On the basis of the material presented, we can draw the following conclusions:

1. Despite the widespread occurrence of sulfate-reducing processes during the Lower Proterozoic, the isotopic composition of sulfur in sulfides of the Ludikovian level was primarily determined by the influence of secondary brines which were products of the metamorphization of Jatulian evaporite formations.

2. The disseminated sulfides of the Khirvinavolok suite in the Kukasozero zone, which show negative $\delta^{34}\text{S}$ values, are an exception. Such an isotopic composition is typical of sulfides formed during stages of diagenesis during the process of sulfate reduction.

3. An analysis of the isotopic composition of sulfur in disseminated sulfides of the Pil'guyarvi suite of the Pechenga structure allows us to conclude that endogenous abyssal sulfur had an influence on its formation.

LITERATURE CITED

1. A. M. Akhmedov, "Epochs of evaporitization in the Early Proterozoic of the Baltic shield," *Dokl. Akad. Nauk SSSR*, **312**, No. 2, 698-702 (1990).
2. V. I. Vinogradov, "The role of the sedimentary cycle in the geochemistry of sulfur isotopes," *Trudy Geol. Inst. Nauk, Akad. Nauk SSSR*, Issue 351 (1980).
3. K. O. Kratts, "The geochemistry of the Karelides in Karelia," *Trudy Laboratorii Geologii Dokembriya*, Issue 16 (1963).
4. V. A. Melezhik and A. A. Predovskii, *The Geochemistry of Early Proterozoic Lithogenesis Based on the Example of the Northeastern Baltic Shield* [in Russian], Nauka, Leningrad (1975).
5. N. I. Moskovchenko and S. I. Turchenko, *Metamorphism of the Kyanite-Sillimanite Type and Sulfide Mineralization* [in Russian], Nauka, Leningrad (1975).
6. V. Z. Negrutsa, *Early Proterozoic Stages in the Development of the Eastern Part of the Baltic Shield* [in Russian], Nauka, Leningrad (1984).
7. V. T. Safronov and G. L. Goroshchenko, "Carbonaceous rocks of the Khirvinavolok suite (Northern Karelia)," *Litol. Polezn. Iskop.*, No. 1, 55-69 (1988).
8. G. Faure, *Principles of Isotope Geology* [Russian translation], Mir, Moscow (1989).
9. G. V. Shat-skii, "The isotopic composition of sulfide sulfur of the Zazhoginsk shungite deposit (Southern Karelia)," *Litol. Polezn. Iskop.*, No. 1, 20-28 (1990).
10. G. V. Shat-skii and G. L. Goroshchenko, "Minerogenesis of the Jatulian formations of the Northern Karelian zone based on the example of the Kukasozero synclinorium," *Litol. Polezn. Iskop.*, No. 6, 107-120 (1991).
11. Ya. E. Yudovich, V. V. Makarikhin, P. V. Medvedev, and N. V. Sukhanov, "Isotopic anomalies of carbon in carbonates of the Karelian complex," *Geokhimiya*, No. 7, 972-978 (1990).
12. A. K. Goodwin, J. C. Monster, and H. G. Thode, "Carbon and sulfur isotope abundances in Archean iron-formations and Early Precambrian life," *Econ. Geol.*, **71**, 870-891 (1976).
13. K. Hattori, F. A. Campbell, and H. R. Krouse, "Sulfur isotope abundances in Archean clastic rocks: implications for the coeval," *Nature*, No. 302, 323-326.
14. I. R. Kaplan and S. C. Rittenberg, "Microbiological fractionation of sulfur isotope," *J. Gen. Microbiol.*, **34**, 195-212 (1964).
15. M. Schidlowski, "Antiquity and evolutionary status of bacterial sulfide reduction," *Sulfur Isotope Evidence in Origins of Life*, No. 9, 299-311 (1979).

GEOCHEMICAL FEATURES OF THE ACTIVE LAYER OF BOTTOM SEDIMENTS

N. G. Patyk-Kara and E. V. Tikhomirova

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Data are presented that demonstrate a unique capacity of the contemporary active layer of bottom sediments to store geochemical information about the underlying strata of the sedimentary mantle, buried oil reservoirs, buried ore bodies or deep-seated dislocation and magma structures. The mechanisms responsible for transmitting the geochemical signal upwards along a rock sequence of near-shore and sea deposits are exhibited.

Because of the advancing frontier of geological prospecting research in the area of the continental shelf, researchers and workers in the field now must develop and employ new high-speed methods of obtaining information about substances in the bottom sediments as well as combine these methods with already known methods of geological surveying of the continental shelf and the search for commercial minerals. Thus, geological investigations of the contemporary layer of bottom sediments found in the coastal shelf are becoming increasingly common. This layer is now the object of large-scale sampling in sounding, navigational, and geological engineering studies, and in mapping of the continental shelf. Because of its easy accessibility, the method has now become the source of the most routinely obtained geochemical information.

It is precisely this layer, the surface layer of the bottom sediments which has undergone systematical roiling, water erosion, and redeposition under the influence of the waves and currents of the sea, which elsewhere has been termed the *active layer* of bottom sediments [12]. The upper boundary of the active layer is the surface of the sea floor; the lower boundary is determined by the depth of propagation of the mechanical action on unconsolidated formations during periods of maximal hydrodynamic activity.

Current interpretations of the migrational capabilities, mobility series, and regional laws of distribution of the chemical elements under the lithological conditions of the coastal shelf are based largely on the work of N. M. Strakhov [16, 17, etc.]. Subsequently, Strakhov's research into the behavior of the elements under different facies conditions of the near-shore shelf was extended by new data [5, 6, 8, 9, 13, 18, 20-22, 24, 25].

Of especial interest are investigations of different geochemical barriers in the seas and oceans in such studies as [3, 5, 11, 23].

The contemporary active layer of bottom sediments constitutes a boundary zone that separates environments with different modes of migration and concentrations of the chemical elements. Variations in the modes of occurrence of different metals extend into the active layer of bottom sediments until an equilibrium between the solid and liquid phases of the deposits and between the interstitial and bottom water is established. In addition, because of the elevated hydrodynamic activity, mechanical differentiation between the elements, which is controlled by the first and second mechanical barriers, occurs in the upper layer of the deposits. A. P. Lisitsyn and E. M. Emel'yanov [10] have suggested referring to these types of boundary zones within which there may appear a host of distinguishable geochemical barriers as *barrier zones*.

THE CONTEMPORARY ACTIVE LAYER AS A CONCENTRATOR OF "DEEP-SEA" GEOCHEMICAL INFORMATION

Until recently the active layer of deposits, like the barrier zones, was considered exclusively in terms of how it reflected processes of contemporary sedimentation and early diagenesis. Nevertheless, on the basis of the significant

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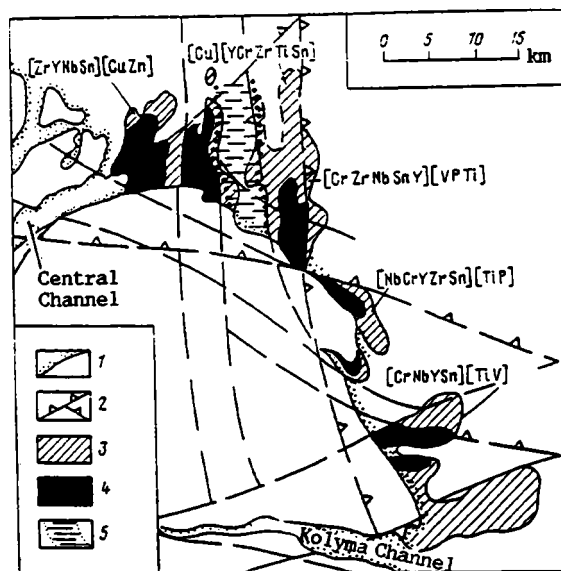


Fig. 1. Complex geochemical anomalies of the intrazonal structure in the bottom sediments of the fore-delta of the Indigirka River: 1) shore line; 2) dislocations with break in continuity; 3, 4) complex geochemical anomalies – (3) weakly contrasting, (4) contrasting; 5) zone characterized by minimal values of V and Ni.

experience that has been gained from lithochemical mapping of regions of the continental shelf in different bodies of water, it would appear that the heterogeneity of the geochemical field of the active layer of bottom sediments may be related not only to contemporary sedimentation; in a number of cases, independently of the scale of the particular investigation, there is no direct and unambiguous relation between this heterogeneity and the contemporary conditions under which sedimentation occurs, nor is there any reflection in the sediments, instead it proves to be "azonal" and discordant in nature relative to the lithodynamic and facies zones.

Let us consider certain examples that illustrate results of regional intermediate- (1:1,000,000 and 1:200,000) and large-scale (1:50,000), and detailed geochemical studies in regions of the arctic seas carried out between 1980 and 1990 under the direction of, and with the direct participation of, the present authors, together with results of samplings performed in the course of a government survey of the shelf. In all the cases the initial data consisted of data from surveys of the surface layer of the bottom sediments, which were analyzed by means of semiquantitative approximate quantitative spectral analysis.

Example 1. In the course of geochemical mapping of the fore-delta of the Indigirka River it was established that the spatial distribution of many of the chemical elements reflects not only the contemporary lithodynamical conditions and distinctive features of the floor topography. The part of the fore-delta which has been studied is characterized by low depths (< 10 m) and relatively subdued topography, the most typical forms of which are shallow troughs, broad shoals, and delta islands. The bottom sediments consist of fine sands and silt and are poorly differentiated in terms of geography.

In addition to low-contrast river-sea type estuarine Cu, Zn, and Pb anomalies and even weaker Zr, V, and Cr alluvial-type anomalies found in the central portions of individual banks in the regions under investigation, extended zones have been identified that are characterized by elevated concentrations of a large number of elements (Fig. 1). The distinctive feature of these zones, which are 6-10 km in width, lies in the fact that they are situated discordantly relative to the shore line; zones of submeridional strike are the most highly pronounced of these zones, while the sublatitudinal zones are less pronounced. The most complex cumulative-type anomalies having the form of Zr, Nb, Y, Sn, and Cr(Ti) are grouped at their points of intersection; along the flanks the composition of the anomalies is noticeably impoverished. Similar regularities are present in the distribution of the other elements, as is observed, for example, in a compact zone characterized by minimal values of V and Ni along a submeridional trend, and crossing a number of different facies regions.

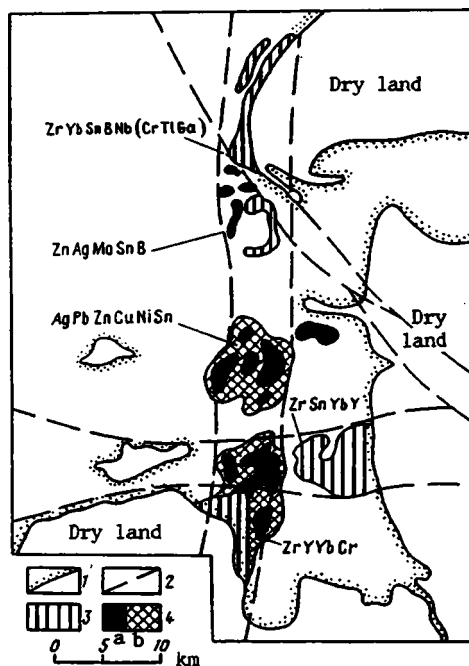


Fig. 2. Complex geochemical anomalies in the active layer of the bottom sediments at points of intersection of ore-control faults (Sellyakh Gulf in the eastern portion of the Laptevye Sea): 1) shore line; 2) dislocations with breaks in continuity; 3) complex alluvial-class anomalies; 4) the same, formed mainly by mobile forms of the elements – (a) high-contrast forms and (b) low-contrast forms.

Extended, highly complex linear anomalies oriented either obliquely or perpendicularly to the shore line may also be distinguished by means of computer processing of data files using the method of principal components, a version of the factor analysis method. The "natural components" of the geochemical field (principal components) represent correlation relations in the field of the initial attributes. Moreover, the first principal component characterizes an association of strongly correlated elements with maximal contrast of the heterogeneous distribution in space. The second and succeeding principal components represent new associations (except for the influence of the degree of correlation with preceding associations) with a gradually decreasing heterogeneity contrast.

Within the sector which we have studied these anomalies were tracked for 6-20 km from the shore and lacked a contour. Comparison of these anomalies to the discontinuous system of regional dislocations led us to hypothesize that they are controlled by flexures and zones of elevated permeability along active faults of the folded base and the sedimentary mantle. The complex composition of the anomalies, which we believe to be a reflection of deep-lying structures situated in the geochemical field, would appear to be determined by their dual origin. On the one hand, they were formed by astatic mobile elements which, we believe, had undergone vertical migration into zones of elevated permeability, and on the other hand, while retaining their tectonic activity, the discontinuous zones of dislocations may play the role of mechanical barriers on which independent centers of erosion are grouped, as a result of which the composition of the structural anomalies and elements of the alluvial class are mutually complementary [14].

Example 2. A rather complex pattern of distribution of the chemical elements in the contemporary active layer was discovered in the course of intermediate-scale geochemical mapping of shallow bays in the Sellyakh Gulf along the eastern shore of the Laptevye Sea. The background consists of a rather regular composition of bottom soils, which appear to be fine sand and silt material and a highly subdued bottom topography. Moreover, as in the preceding case, it turned out that the anomalies, which are connected to the contemporary facies conditions, are, as a rule, low contrast. Such is the form of the lens-shaped Ti, V, Mn, and Cr type anomalies, which coincide in space with drowned valleys in the central portion of the gulf, as well as weak Cu, Zn, and Pb estuarine anomalies facing the mouths of the Maksunuokh and Chondon rivers.

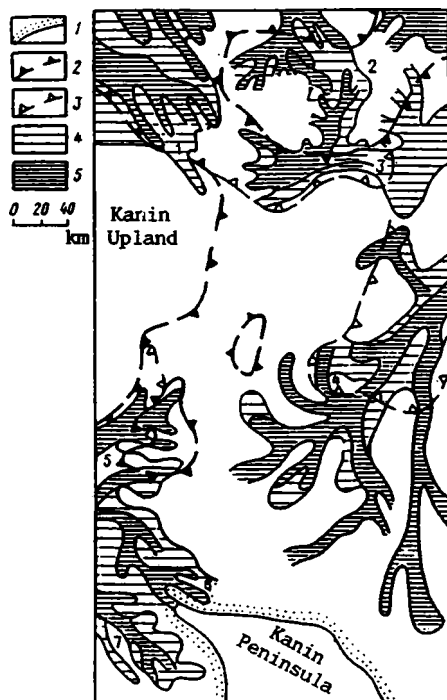


Fig. 3. Districts of correlative aggradation of a broad complex of chemical elements in the bottom deposits of the Barents Sea, identified by the method of principal components: 1) shore line; 2) arched uplifts; 3) depressions in the original bed; 4, 5) complex geochemical anomalies – 4) low-contrast anomalies and 5) high-contrast anomalies which coincide with the position of buried valleys. Numerals 1-7 in the diagram correspond to the number of the anomaly.

In addition to the above types of anomalies, geographically extremely broad ($n \cdot 10 \text{ km}^2$) contrasting multicomponent anomalies without any direct connection to the contemporary bottom topography or lithofacies have also been identified. As noted earlier, these include dual types of objects [14]. The Zr, Sn, Y, and Yb type anomalies belonging to the alluvial class are mechanical in nature and retain a relative build-up of heavy minerals on the structural barriers within the relatively uplifted blocks. Such is the form of the geographically extended anomaly along the eastern shore of the Sellyakh Gulf, which would appear to have its origin in ore deposits, moreover, it may have been produced out of the erosion of more ancient metal-bearing (stanniferous) deposits. The Ag, Pb, Zn, Cu, Ni, and Sn type anomalies, which consist of mobile elements and actively absorbed clay and organic matter [15], have a less well-defined character. A typical feature of their relative position within the bay is their confinement to points of intersection of regional faults of submeridional and sublatitudinal strike that extend from the dry land (Fig. 2).

The formation of secondary lithochemical anomalies on top of discontinuous dislocations has virtually never been discussed in the literature, with the exception of the data of A. A. Bezborodov and O. V. Emel'yanova [4], who pointed out a connection between a broad (6-10 km) bandlike geochemical anomaly in the bottom sediments of the Feodosii Bay and the Parpach dislocation extending from the bay.

The examples which have been presented here show that the block structure of the Pre-Cenozoic basement may be reflected in the geochemical field of the bottom sediments. Moreover, under certain conditions only geochemical methods enable us to demarcate the relatively uplifted and relatively submerged tectonic blocks, inasmuch as the Pre-Cenozoic block tectonics is not manifested either in the contemporary topography nor in the distribution of the lithological varieties of contemporary deposits. In particular, it was established that in the general case districts of correlative aggradation correspond to relatively submerged tectonic blocks, while districts characterized by the evacuation of a broad complex of elements that may be identified as the first principal component, correspond to relatively uplifted tectonic blocks.

Examples may also be presented which, in the geochemical field of contemporary deposits, serve to "expose" other types of buried geological bodies.

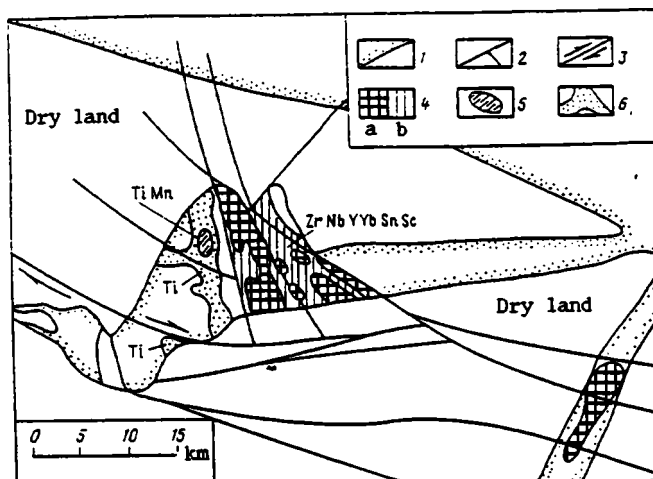


Fig. 4. Cross-cutting azonal geochemical anomalies in the bottom sediments of the Omulyakh Gulf (Eastern Siberian Sea): 1) shore line; 2) dislocations with breaks in continuity; 3) shifts; 4) complex alluvial-class anomalies on the structure barrier – (a) contrasting anomalies; (b) low-contrast anomalies; (5) and (6) anomalies – (5) titanium and manganese; (6) titanium.

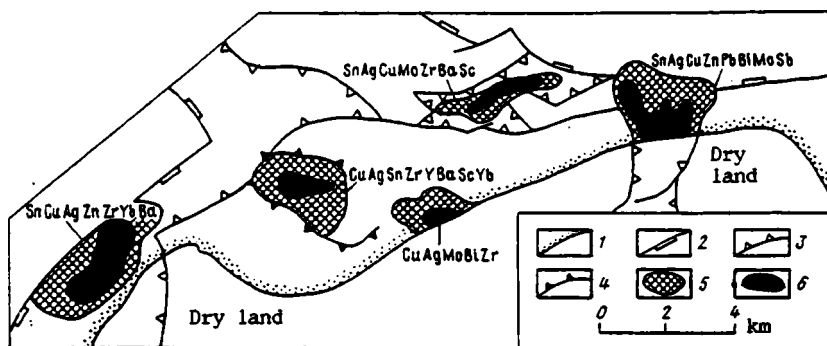


Fig. 5. Complex type anomalies that appear to have originated in ore deposits in the active layer of bottom sediments along the northern shore of Great Lyakhov Island: 1) shore line; 2-4) boundaries – (2) Paleogene trough; (3) buried fault trough basins; (4) domes; (5) and (6) complex anomalies – (5) low-contrast anomalies; (6) contrasting anomalies.

Example 3. Regional geochemical investigations were carried out in the Barents Sea in a survey of the contemporary bottom sediments at the first level of heterogeneity identified by the first principal component. A system of braided "dendritelike" anomalies whose morphology led us to conceive of a connection to a valley network (Fig. 3) was mapped within a stratified subaqueous leveled plain as part of this survey. Comparison of the anomalies to data gathered in the course of seismic profile shooting confirmed that they are located above the large buried valleys without being directly reflected in either the floor topography or in the lithology of the contemporary sediment.

Example 4. Turning to anomalies at larger scales, we were also able to discover that low-contrast lens-shaped Ti, Mn, and (V, Cr) type anomalies 3-4 km in extent are found in the bottom sediments of semidetached bays and gulfs. Sometimes they spatially coincide with drowned submarine valleys, in other cases, for example, in the Omulyakh Gulf, they occupy an intersecting position and, on the basis of paleogeographic reconstructions, coincide spatially with the buried valleys that cross the bay. Moreover, in the latter case it has been possible to delineate a shift in the anomalies relative to each other through a large regional fault zone running from west to northwest. From regional paleodynamic reconstructions relative to the shelf of the eastern Arctic Seas, it was established that the transcurrent movements along faults in

TABLE 1. Structure and Composition of a Geochemical Anomaly of Mixed Origin Formed in the Surface Layer of Bottom Sediments in Erosion and Redeposition of Material from a Crust of Weathering (section of Eastern Boruoga, and the North Lyakhov district; studies performed at a 1:50,000 scale)

Anomaly as a whole		Interior maximally contrasting district of anomaly	
element	background-normalized contents* (KK)	element	background-normalized contents (KK)
Ba	4,95	Ba	5,5
Zr	4,68	Y	5,0
Cu	4,05	Zr	5,0
Sc	3,84	Sc	4,56
Y	3,47	Yb	4,0
Yb	3,05	Cu	3,5
Ag	2,47	Ag	2,0
Ti	1,79		
Co	1,79		
Ga	1,74		
Mn	1,68		
Cr	1,68		
Ordered series	Ba _{4,95} Zr _{4,7} Cu _{4,05} Sc _{3,8} Y _{3,5} Yb ₃ Ag _{2,5} (TiCO) _{1,3} Ca _{1,7} (MnCr) _{1,68}	Ordered series	Ba _{5,5} (YZr) ₅ Sc _{4,6} Yb _{4,6} Cu _{3,5} Ag ₂

*From data of an approximate quantitative spectral analysis.

this trend would have to be attributed to the Miocene era; this leads us not only to hypotheses concerning the age of the buried valley (Eocene to Oligocene?), but also to computations of the relative rate of horizontal shifts along the fault, which amounts to more than 1.2 cm per 1000 years (Fig. 4).

Examples may also be presented that illustrate the emergence in the contemporary active layer of complex geochemical anomalies that appear to have originated in ore deposits and that have been created on top of buried ore bodies. Some of them, particularly the Ag × Zn × Mo type anomalies, have been described previously [7].

Example 5. This pattern is still more clearly expressed along the northern shore of the Great Lyakhov Island. A large number of tin streams and tin ore manifestations have now been discovered on the shelf of the island. They are also been found in the buried state and are covered by nonmetalliferous or slightly metalliferous "peats" (Upper Pleistocene), contemporary fine-grained sand, and silt 10-25 m in thickness. These anomalies were all formed by elements of ore paragenesis present in different concentrations or ratios, including B, Pb, Zn, Nb, Sn, Bi, Sb, Ag, Mn, and Cu (Fig. 5).

Anomaly 1 is situated on the rear flank of the district within the Boruoga shallows. Within this anomaly the Zn contents reach 500-1000 g/ton in the contemporary active layer; the KK concentration coefficients are also high: for Cu, 3.8; for Ag, 3.6; for Mn, 2.5; and for Nb, 2. A tin stream spatially conjugate to the original source was discovered by prospecting work in the underlying deposits. A less contrastive anomaly with analogous composition (KK: Sn, 2; Ag, 2.5; Mn, 2.1; Cu, 4; Ba, 5.5) is situated in the central portion of the Boruoga Shallows. Over the central portion of the Eterikan depression there is also an enclosing buried placer; it is characterized by the following values of the KK: Pb, 2.0; Bi, 2.3; Nb, 1.2; Cu, 4.6; Ag, 1.6; Sn, 3.6; and Mn, 2.6; moreover, it recalls the outlines of a buried depression, though in subdued form. The Sn contents in the bottom samples within the anomaly reach 100 g/ton. Whereas the underlying deposits are represented by nonstanniferous complexes, the anomalies in the active layer assume the form given in Table 1. Finally, even further to the east (mouth of the Little Kutta River) there is yet another contrastive anomaly (Sn, 16; Pb, Ag, Cu, and Mn, 3; Nb, 2; Zn and Bi, 1.7 and 1.2, respectively) genetically associated with a buried tin stream. Note, however, that, unlike the anomalies which we have described up until now this anomaly is of mixed origin, with contemporary abrasion processes and evacuation of metalliferous material from the Little Kutta River playing roles in the formation of the anomaly.

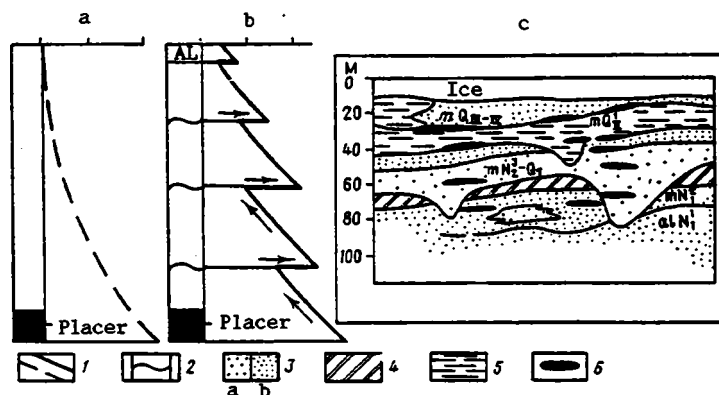


Fig. 6. Mechanism responsible for the formation in the active layer of "supra-placer" mechanical-type anomalies in a continuous fracture (a), in the presence of local erosions (b), and relative location in the sequence of suspended concentrations of heavy minerals (c): 1) contents of elements forming "alluvial" class anomalies; 2) erosion boundaries; 3) sand - (a) fine sand; (b) medium-grain sand; 4) loam; 5) silt; 6) concentrations of heavy minerals. AL) Active layer.

MECHANISM OF TRANSMISSION AND STORAGE OF GEOCHEMICAL INFORMATION IN THE ACTIVE LAYER

The examples which we have considered show that under the conditions of sedimentation typical of the near-shore shelf, special mechanisms of vertical migration of matter are involved, leading to a relative concentration of the chemical elements in the surface layer of bottom sediments that have no direct connection to the contemporary lithodynamical and facies disposition. One consequence is that, in the contemporary active layer, complex geochemical anomalies are found which turn out to represent indicators of buried reservoirs (valleys, structural depressions), dislocations with breaks in continuity, and buried ore bodies.

It would appear that this type of transmission of geochemical information occurs along at least two paths - in mechanical form and in the form of mobile compounds.

The prerequisites for *mechanical vertical migration* of the chemical elements, i.e., upwards displacement through a column of detrital minerals which constitute the "carriers" of a large number of chemical elements occurring as part of complex anomalies characteristic of the active layer, are given by the properties of the active layer itself. It is known that the thickness of the active layer in the near-shore zone, which depends on the dynamical conditions and the hydraulic coarseness of the displaced migrated deposits, does not, in the general case, exceed several dozen centimeters, though it may grow significantly in periods of extremal sea conditions. This is attested to by the graduated classification of material observed in a layer 1.5-2 m and more in thickness, in particular, the relative enrichment of the basal levels of the active layer with heavy minerals.

Because of these properties of the active layer, K. V. Yablokov was led to conclude that in a continuous sea section the basal level (of the active layer) is enriched with stable minerals from the underlying deposits [19]. In turn, this level serves as a source for the enrichment, with heavy minerals, of a new active layer, which, in general, is responsible for the mechanism of vertical migration of graded packets of heavy minerals upwards through a column of near-shore and marine sediments, a process that dampens upon cessation of the "marine" regime of sedimentation. In this case the highest concentrations of chemical elements migrating predominantly with detrital minerals, mainly Zr, Y, Yb, Nb, Ti, La, and Ce, as well as Sn and B, are confined to the basal level of the active layer, a phenomenon which it is possible to observe in layer-by-layer sampling of the active layer. Such data, in particular, were obtained in the course of the present authors' sampling of bottom sediments of the Ebelyakh Gulf in the eastern portion of the Laptevye Sea.

Obviously, the effectiveness with which the "signal" is transmitted depends on the structure of the column [26]. The mechanism may be conceived of by assuming that there occurs a process by which the underlying strata are subjected to wave treatment, resulting in a distinctive type of mineralogical and geochemical "legacy" of active layers with respect to the underlying strata. With build-up of masses of sediment, however, this signal will weaken due to the fact that the basal level of the active layer that is most enriched with heavy minerals will, in turn, be "withdrawn" from the scope of wave treatment. Amplification of the signal may occur at the abrasion level and under other circumstances in which there is observed predominant evacuation of light clastogene particles and residual accumulation of heavier minerals. This mechanism of secondary enrichment promotes the formation of allochthonous concentrations of stable heavy minerals and geochemical anomalies corresponding to them in the rock sequence, something significantly separated along the vertical from the initial ore body (Fig. 6). One example of such allochthonous concentrations are the "suspended" stanniferous lens with Sn content of several hundred grams per cubic meter and the low-contrast Zr, Sn, Y, Yb, and B type geochemical anomalies that are formed at different levels of the sequence of Late Cenozoic near-shore and sea deposits in the Naga and Turukty district near the eastern shore of the Sellyakh Gulf in the Laptevye Sea.

It may be supposed that the greater the local erosion in the stratum of near-shore and coastal sediment, the more clearly manifested is the process. Apparently, in addition to other conditions these local circumstances would have to distinguish relatively uplifted blocks, flexures, and zones of relatively high-gradient movement at the boundaries between the blocks. This is precisely the character of the alluvial class Yukagir anomaly found along the shores of the Sellyakh Gulf which we described earlier (cf. Fig. 2). Recently, together with Yu. L. Fotina, the present authors obtained explicit data that confirm that complex alluvial-type geochemical anomalies having the shape of columns were formed in a stratum of near-shore and sea deposits above zones of tectonic scarps.

The presence of a thick complex physicochemical barrier arising at the boundary between sediment and bottom water represents a prerequisite for ascending migration of *mobile forms of the elements* and their concentration in a near-surface layer of the active layer. In this case there are anomalies consisting of Cu, Pb, Zn, Mo, Ag, Be, Co, and other mobile (i.e., in the sense of N. M. Strakhov) elements.

Secondary dispersion halos over buried placers and native ore manifestations [7] are the most instructive example of the result of the physicochemical processes involved in the transmission of depth geochemical information. Moreover, their complex composition has led us to suppose that genuine solutions or a colloidal phase that form lateral and vertical migrating streams play a significant role in their formation, together with mechanical transport (diffusion of small mineral waste). In particular, the rise of matter in the halos of an ascending migration would appear to be determined principally by diffusion in aqueous and gaseous media and by capillary ascent of solutions. Data on the Val'kumei sea-beach placer in the Chaun district, where water extracts withdraw up to 30% of all the Mo contained in the sediment together with some fraction of the Zn, Pb, and Cu, may represent an immediate demonstration of the fact that mobile forms of the elements are present in significant quantities in the "supra-placer" halos of buried placers. In [15] data are presented which demonstrate that tin accounts for from 60 to 80% of the hydrogenic form of Cu in the halo of a submerged and buried placer.

Ionic exchange, electrochemical phenomena, and osmosis, phenomena which occur at the freezing and thawing front in permafrost, play no little role in the formation of an ascending flow of mobile forms of the chemical elements in a stratum of the sedimentary mantle. Variations in the rate of salination and in the composition of salts that occur at the interface between phase transitions (from hydrocarbonate calcium salt to chloride magnesium-sodium salt in the course of freezing), which are especially noticeable under the conditions of a closed system, are accompanied by redistribution of dissolved matter between frozen rock, ice, and the residual solution. and activate exchange-absorption processes and promote the passage of a portion of the metals into mobile forms.

From this point of view such episodes in the Quaternary history of the arctic shelf as repeated regressions and transgressions of marginal basins, accompanied by the formation and degradation, respectively, of permafrost ground, which do not have the capacity to leave traces in the structure of ascending flows of mobile forms of the chemical elements, are of especial interest. The process of extraction of metals apparently is repeatedly amplified in the local circumstances of the near-shore zone, where local chambers of saline pressure water at negative temperatures distinguished by a high level of corrosiveness could have formed in the course of freezing [1, 2].

An important role in understanding the indicative geochemical properties of the active layer is performed by the "stability" of geochemical anomalies of deep-seated origin. The mechanism responsible for the formation of mechanical-type anomalies itself tends to concentrate heavier minerals at the base of the active layer and promotes their relative

stability under the conditions of variable dynamic circumstances. This also confirms data that were obtained by K. V. Yablokov in repeated surveys of the Chokurdakh placer deposit, which demonstrated that the Sn, Pb, and Cu anomalies associated with the granular part of the sediment were not disturbed from one storm to the next, and only their outline varied.

Apparently, following A. P. Lisitsyn and E. M. Emel'yanov [10], the active layer should be considered as a geochemical barrier zone in which there are, besides a mechanical barrier, also absorptive, alkaline, electrochemical, and certain other types of physicochemical barriers. The "conserving" influence of the sea environment also promotes contrastive manifestations of anomalies in the active layer. It is typical that previously formed anomalies break down quite rapidly in the cases which we have studied as soon as subaerial circumstances are established. Moreover, they retain their distinctiveness at the surface of the contemporary dry land, though break down into smaller anomalies that are more impoverished in terms of the composition of the contour within the limits of the surface occupied by the sea in the Upper Pleistocene.

* * *

Thus, the contemporary active layer of bottom sediments of the near-shore shelf possesses the unique capacity to accumulate geochemical information about the underlying level of a sedimentary mantle, buried reservoirs, buried ore bodies, and deep-lying discontinuous and focal structures.

Because of the elevated sensitivity of the active layer to geochemical signals from the depths, secondary dispersion halos are able to form not only over contrastive sources, but also over dislocations with breaks in continuity, which happen to be zones of elevated permeability, as well as over buried accumulator bodies characterized by concentrations of the chemical elements that are elevated relative to the background.

The transmission of geochemical information is performed both by mechanical means and in the form of mobile compounds. It has been established that the efficiency of the former process promotes the presence of erosion boundaries in a friable mantle section on which local alluvial class geochemical anomalies form. The presence of a complex physicochemical barrier, formed in the interaction between sediment and bottom water, is a prerequisite for ascending migration of mobile forms and their concentration in the active layer. Of no little importance in the formation of an ascending flow of mobile forms of the chemical elements on the Arctic shelf are the physicochemical processes that occur at the freezing (thawing) front, the passage of which through a stratum of detrital deposits reflects a shift in the cryogenic circumstances in the alternation of regression and transgressions.

The continuity of the chemical composition of the active layer relative to the underlying sediment significantly expands the potential for application of geochemical methods in marine prospecting efforts, permitting the active layer to be used as an indicator of special features of the structure of a sedimentary mantle, of the structural and geomorphological heterogeneities of the near-shore shelf, and of accumulations of minerals.

LITERATURE CITED

1. N. P. Anisimova, "Seasonal variations of the chemical composition of bodies of liquid saline water (temperature below 0°C) of alluvial deposits," *Hydrogeological Investigations of a Permafrost Zone* [in Russian], Institute for Permafrost Studies, Siberian Division, USSR Academy of Sciences, Yakutsk (1976), pp. 36-46.
2. N. P. Anisimova and N. F. Grigor'ev, "Chemical composition of the bottom sediments in a near-shore section of the Kara Sea," *Migration of Elements in a Permafrost Zone* [in Russian], Nauka, Novosibirsk (1985), pp. 71-78.
3. T. A. Aizatullin, V. L. Lebedev, I. A. Suetova, and K. M. Khailov, "Boundary surfaces and the geography of the ocean," *Vestn. Mosk. Gos. Univ. Ser. Geogr.*, No. 3, 25-35 (1976).
4. A. A. Bezborodov and O. V. Emel'yanova, "Connection between anomalies in the microelement composition of sediments in the Kerchen-Taman shelf to fault zones and near-shore outcrops," *Dokl. Akad. Nauk Ukr. SSR*, No. 4, 3-7 (1985).
5. E. M. Emel'yanov and V. N. Lukashin (eds.), *Geochemistry of Sedimentary Processes in the Baltic Sea* [in Russian], Nauka, Moscow (1986).

6. V. V. Gordeev and A. P. Lisitsyn, "Mean chemical composition of suspensions of the world's rivers and delivery of sedimentary material from rivers to oceans," *Dokl. Akad. Nauk SSSR*, **238**, No. 1, 225-228 (1978).
7. S. V. Grigoryan and N. G. Patyk-Kara, "Geochemical zonality of placers and its cause," *Dokl. Akad. Nauk SSSR*, **278**, No. 5, 1192-1195 (1984).
8. E. M. Emel'yanov, *Sedimentation in the Basin of the Atlantic Ocean* [in Russian], Nauka, Moscow (1982).
9. A. P. Lisitsyn, *Processes of Oceanic Sedimentation* [in Russian], Nauka, Moscow (1978).
10. A. P. Lisitsyn and E. M. Emel'yanov, "Geochemical interpretation of oceanic and marine geochemical barriers and barrier zones, their classification and role in sedimentation and ore formation," *Geology of the Oceans and Seas*, Vol. 1 (Proc. 6th All-Union School of Marine Geology), Moscow (1984), pp. 220-222.
11. A. S. Monin and E. A. Romankevich, "Problems of the biochemistry of the world ocean," in: *Modern Problems and Topics in Biogeochemistry* [in Russian], Nauka, Moscow (1984), pp. 74-82.
12. *Marine Geomorphology. Terminological Handbook. Near-shore Zone: Processes, Concepts, Definitions* [in Russian], Mysl', Moscow (1980).
13. V. I. Novikov and M. G. Palanskii, "Microelements in contemporary bottom sediment of the Dnepr-Bug drowned river," in: *Petrology, Mineralogy, and Ore Formation in the Ukrainian Shield* [in Russian], Naukova Dumka, Kiev (1984), pp. 87-95.
14. N. G. Patyk-Kara, "Geochemical criteria for prospecting activities and the evaluation of placer deposits in the near-shore zone of the shelf," *Sov. Geol.*, No. 5, 74-87 (1987).
15. N. G. Patyk-Kara, L. P. Dolgoplova, and L. I. Serdobova, "Forms of occurrence in the distribution balance of chemical elements functioning as indicators in tin streams," *Litol. Polezn. Iskop.*, No. 2, 23-35 (1990).
16. N. M. Strakhov, *Problems of the Geochemistry of Contemporary Oceanic Lithogenesis* [in Russian], Nauka, Moscow (1976).
17. N. M. Strakhov, "The geochemistry of contemporary sedimentation," in: *Oceanology. The Chemistry of the Ocean* [in Russian], Vol. 2, Nauka, Moscow (1979), pp. 9-239.
18. V. N. Kholodov and D. S. Turovskii, "Problem of sedimentation in the Caspian Sea. I," *Litol. Polezn. Iskop.*, No. 17, 17-34 (1985).
19. K. V. Yablokov, "Use of the results of studies of the active layer of marine sediment for paleogeographic reconstruction," 27th International Geological Congress (Reports Vol. 1, Section 03) (1984), pp. 426-427.
20. M. H. Bother, P. J. Aruscavage, W. M. Ferree, and P. A. Baedecker, "Trace metal concentrations in sediment cores from continental shelf at the south-eastern United States," *Estuarine and Coast. Mar. Sci.*, **10**, No. 5, 523-541 (1980).
21. S. E. Calvert, "The mineralogy and geochemistry of near-shore sediments," *Chem. Oceanography*, **6**, 187-280 (1976).
22. R. J. Davies-Colley, P. O. Nelson, and K. J. Williamson, "Copper and cadmium uptake by estuarine sedimentary phases," *Environ. Sci. Technol.*, **18**, No. 7, 491-499 (1984).
23. R. A. Horn, *Marine Chemistry*, Wiley-Interscience, New York (1969).
24. D. H. Loring, "Distribution and partition of cobalt, nickel, chromium, and vanadium in the sediments of the Saguenay fjord," *Can. J. Earth Sci.*, **13**, No. 12, 1706-1718 (1976).
25. D. H. Loring, "Geochemistry of zinc, copper and lead in the sediments of the estuary and open gulf of the St. Lawrence," *Can. J. Earth Sci.*, **15**, No. 15, 58-69 (1978).
26. N. G. Patyk-Kara, E. V. Tickomirova [Tikhomirova], and K. V. Yablokov, "Geochemical features of present active layer — indicator of structural and lithodynamical features of nearshore zone," XIII INQUA Cong. (abstracts), Beijing (1991).

EVGENIYA VALERIANOVNA RUKHINA



The science of lithology suffered a heavy loss on November 24, 1992, with the death of Evgeniya Valerianovna Rukhina, a well-known specialist in Quaternary geology and lithology and the founder of the field of the lithology of glacial deposits. Dr. Rukhina pursued this field of research throughout her career and remained creative in the last days of her life.

Dr. Rukhina lived a long and difficult life full of extraordinary challenges. She was born in 1909 in the town of Grodno, graduated from high school in St. Petersburg, and became a student at the Junior College of Topography in 1929, which she left in 1932 to enter the department of geology, soil science, and geography and major in Quaternary geology at Leningrad University, where she met her husband, Lev Borisovich Rukhin, then a student. She began graduate studies at Leningrad University in 1936. In 1940, she achieved the degree of candidate of science and defended a dissertation on "The Upper Cretaceous of the Western Mugodzhary Mountains."

From 1939 to 1942, Dr. Rukhina was a junior research scientist at the Leningrad Mining Institute. Her career was interrupted in the summer of 1941, when she joined the Volunteer Corps and took part in combat near Gatchina and Taitsy.

A new stage in her creative career began in 1942, when she and her husband were evacuated to Saratov, where she worked as an assistant professor in the department of general geology at Leningrad University (relocated there during the war). She became an associate professor in 1946 and a member of the senior research staff of the Institute of the Earth's Crust in 1953. At the end of her scientific career, she was a senior consulting scientist at the Laboratory of Paleogeography there. She did her most important work there, two books entitled "The Lithology of Moraine Deposits" and "The Lithology of Glacial Deposits." She defended her doctoral thesis on "The Lithology of Glacier and Water-Glacier Deposits in the Valdai Glaciation Region" in 1965.

Dr. Rukhina was a prominent specialist in Quaternary geology and was elected a corresponding member of the International Association of Quaternary Geologists in two sections. She was the official reviewer for many dissertations and provided frequent consultations on the lithology of Quaternary deposits for various organizations. She had many disciples and followers. She produced more than 100 publications on the lithology of Quaternary deposits, and she presented a great number of reports at meetings, seminars, and international conferences.

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Dr. Rukhina was also a lithologist with a general profile. Together with her husband, she studied the Paleozoic of the northwestern East European Platform and the Cretaceous of the Fergana Valley (which produced the monograph on "Cretaceous Deposits of the Fergana Basin"). She revised and wrote additional chapters for the second edition of "The Fundamentals of General Paleogeography" and the second and third editions of "The Fundamentals of Lithology" written by her husband.

Evgeniya Valerianovna Rukhina was a friendly, gregarious, and charming person, and her memory will be cherished by her friends and colleagues, who were fortunate to have known her.

*The Editorial Board of Lithology and Mineral Resources
Interdepartmental Committee, Russian Academy of Sciences*

VIKTOR IVANOVICH POKRYSHKIN



Viktor Ivanovich Pokryshkin, doctor of geologic-mineralogic sciences, senior scientist of the All-Russian Institute of the Geology of Foreign Nations, and an eminent specialist in the geology and lithology of phosphorites died suddenly on October 22, 1992. He was born on October 25, 1930, in Novosibirsk. After graduating from the Novosibirsk Geologic Exploration Junior College in 1951, he entered the Moscow Geologic Exploration Institute, from which he graduated in 1956, specializing in the geology and exploration of fossil minerals.

He was a geologist in the Fourth Geological Department of the Ministry of Geology of the USSR from 1956 to 1962, working in China in 1956-57 and in Syria in 1958-62, where he was involved in exploration and prospecting of phosphorite deposits. This work was origin of his special interest in phosphorites, which became the area in which he specialized for the rest of his life.

Dr. Pokryshkin worked in Cuba from 1962 to 1967 as a geologist with the All-Union Aerogeological Trust on reconnaissance of phosphorite fields and exploration of kaolin deposits. His papers on Cuban phosphorites appeared in the Cuban journal *Tecnologica* in 1966 and 1967. The Rio del Cayeján deposit, explored by him, still in operation, is the main source of raw material for the nearby kaolin factory.

Dr. Pokryshkin became a member of the staff of the Institute of Geology of Foreign Nations in 1967, where he remained for twenty-five years and became a leading researcher and well-known specialist in geology of phosphate deposits. He traveled as an expert to Syria, Ethiopia, Libya, Mongolia, and China, and was involved in phosphorite projects in Egypt and Mauritania as well.

In 1970, he completed his candidate of science dissertation, entitled "Geologic Distribution of Upper Cretaceous and Paleogene Deposits in the Eastern Mediterranean Region."

He published many papers in geology, exploration and reconnaissance methods, and geologic/economic assessment of the phosphorites of the Eastern Mediterranean region and the Arabian/African phosphorite-bearing province during the seventies and eighties, where he described such topics as the tectonic and paleogeography conditions of the formation of phosphorites, their composition, and the role of upwelling in phosphogenesis.

He published a monograph entitled "The Distribution Patterns of Commercial Precambrian and Phanerozoic Phosphorite Deposits in the World" in 1981, which has become an internationally acclaimed reference for phosphate

geologists. This was the core of his doctoral thesis, entitled "The Distribution Patterns and Formation Conditions for Phosphorite Deposits of the Arabian/African Province."

In a series of papers and in his candidate and doctoral dissertations, Dr. Pokryshkin elaborated various aspects of phosphate geology. He demonstrated that the Upper Cenomanian and Paleogene phosphorite deposits occur in tectonically different conditions within the African-Arabian Platform, the Atlas epiplatformal folded region, and the Atlantic zone of periocenic subduction. He established the lithologic and paleotectonic regularities of the distribution of phosphorite formations and the paragenetic correlation of granular phosphorites with the silicic-terrigenous-carbonate group of deposits in platformal sedimentation settings. He developed and elaborated the ideas of N. S. Shatskii, who was the first to refer the phosphorite formations of Northern Africa to the terrigenous-carbonate group.

Pokryshkin made noteworthy observations on the cyclic structure of phosphorite-bearing horizons which reflect the periodic succession of marine sedimentation settings. He gave numerous examples to illustrate how basal (more terrigenous) cycles are succeeded periodically and consistently by phosphate cycles.

He believed that phosphate accumulation was determined by the paleogeography of the oceanic shelves of the Thetys and the Atlantic which formed along the margins of the Arabian/African continent. In reconstructing these settings, he established that they included phases of major regional transgressions of the Atlantic and Thetys, which were interrupted by regressions, and he described the aridity of the equatorial climate, the morphology of the shelf regions, and the magnitude and intensity of upwellings.

Dr. Pokryshkin made a major contribution to our understanding of the processes and regularities of the formation and distribution of phosphorite deposits on a global scale as well, since the principles and patterns established in the Arabian/African province were found to be applicable to other phosphorite-bearing regions.

He planned an important paper on potential sources of phosphorus and its deposition pathways in the phosphorite-bearing basins of the Cenomanian-Paleogene of the Arabian/African province for the symposium on phosphorites and phosphogenesis held in August 1992 by the Phosphorite-Bearing Section of the Interdepartment Lithology Committee of the Russian Academy of Sciences in Moscow. His deteriorating health prevented him from presenting this work. The abstract of this paper, his last publication, discusses the sources of phosphorus, pointing to the synchronism of Late Cenomanian-Paleogene phosphorite formation and Late Cretaceous-Paleogene magmatic activity in the Mediterranean ophiolite belt and the continental rift zones of Africa and Arabia. He noted the coincidence of the time of active development of peneplanation surfaces and the laterite crusts of weathering in the equatorial Arabian/African peneplain. According to his theory, the rifting of the Atlantic Ocean and Thetys during the epoch of phosphate accumulation could have been conducive to release of endogenous phosphorus into seawater brought by upwellings into shelf zones. He saw confirmation of this hypothesis in the high phosphorus contents in the alkaline basalts of the Mediterranean ophiolite belt, which may have been a supply source of phosphorus and silica for the oceanic water reservoir. Laterite crusts of weathering would have served as a subsidiary source.

He noted that the special interest in phosphorus sources stemmed from the problems in the genesis and evolution of phosphorite accumulations, which, as demonstrated by A. V. Kazakov, can be interpreted with special reference to major phosphorite-bearing regions, including the Arabian/African province.

Pokryshkin was a regular active participant in scientific conferences on phosphate geology. On many occasions, he represented Russia at field seminars under the International Phosphorite Project No. 156 in India, China, and Mongolia. He was a permanent and active member of the Phosphorite-Bearing Section of the Interdepartment Lithology Committee of the Russian Academy of Sciences.

Dr. Pokryshkin published more than 80 works, mostly concerned with the geology of phosphorite-bearing deposits. He was a dedicated phosphorite geologist who made major and useful contributions to the field.

The memory of Viktor Ivanovich Pokryshkin as a geologist, scientist, and human being will long remain in the hearts of all who knew him.

*The Editorial Board of Lithology and Mineral Resources
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